III.1. CROSS-SBA Publications by GEO-BENE Consortium Partners

Global Earth Observation – Benefit Assessment: Now, Next, and Emerging

GEO-BENE global database for bio-physical modeling v. 1.0

(Concepts, methodologies and data)

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Summary:

Digital database presented here was compiled as a purposeful dataset which is to support GEO-BENE project activities targeted towards societal benefit assessment of improved information coming from data-model fusion approach applied in agriculture and ecosystem modeling. Version 1.0 of the global database is the first approximation to bio-physical model EPIC and agricultural and forestry sector optimization model FASOM requirements and a potential of available global observation data and data coming from other sources addressing climate, topography, soil, and crop management. Several hierarchically organized spatial reference objects were defined to geographically display the global database data. The global scale 5' spatial resolution grid covering land surface was created as primary spatial reference for geographical representation of all other spatial objects. Homogenous response units, 30' spatial resolution grid and country-level administrative units serve the secondary spatial reference as well as the basis for delineation of elemental spatial units (tertiary reference) for ultimate spatial geographical representation and organization of data in the global database. Global scale and publically available data sources used for global database compilation were described and classified into four groups (global observation data, digital maps, statistical and census data, and results of complex modeling) for the better understanding of the present situation in sources of the data available for global scale agro-ecosystem modeling. Data treatment and interpretation methodologies and the way of data harmonization are described so that solid metadata basis is available for the data publication and exchange. Global database comprises four thematic datasets addressing all global modeling aspects being under consideration: (i) land cover/land use statistics dataset, (ii) topography and soil data dataset, (iii) cropland management dataset, and (iv) climate dataset. Self-standing (v) spatial reference dataset provides a tool for geographical representing and visualization of the data. Data structure of all the datasets – tables and attributes – is also identified and described in the technical report.

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1. Introduction

Global database for bio-physical modeling (further referred as global database) described here has been created within 7th EC framework program project GEO-BENE (*Global Earth Observation – Benefit Assessment: Now, Next, and Emerging*, http://www.geo-bene.eu/).

Global database is primarily supposed to support the data-model fusion approach in agriculture sector modeling based on bio-physical model EPIC - ***E**nvironmental **P**olicy **I**ntegrated **C**limate* (Williams et al., 1995) and the data on soil, topography, climate, land cover and land use available at global scale. Global database should serve also as a source of data on land cover/land use for land use optimization modeling with FASOM model - *Forest and Agricultural Sector Optimization Model* (Adams et al. 1996). Along with its main purpose, the global database is also a tool for identification of the gaps in availability of necessary global data for successful data-model fusion based interpretations in societal benefit area (SBA) agriculture (Justice et Becker-Reshef, 2007) and this way to support the GEO-BENE participation on a Group on Earth Observation (GEO) activities.

Data-model fusion based geographical modeling of landscape is not a straightforward task. Depending on particular circumstances, it requires more or less complex approach to gather all the necessary input information on landscape and natural or human-driven landscape processes which is consequently used to carry out appropriate basis for (bio-physical) model application and interpretation of the modeling results (c.f. Rossiter 2003). For global-scale modeling, however, it is not possible to gather directly measured input data in such a spatial, temporal and attribute detail which can fully satisfy the requirements of the (bio-physical) model.

This implies that current version of the global database (version 1.0) can be considered only a broad approximation to an optimal landscape model necessary for the fully successful application of (bio-physical) model and rather than real requirements of (bio-physical) model or complex landscape modeling it reflects a compromise between the needs and limits:

- **general modeling requirements** – (needs) - *a)* global-scale geographical landscape modeling, *b)* implementation of base-run and alternative scenarios for climate, land cover and (arable) land management into the modeling, *c)* (optional) clustering of EPIC and FASOM model within a complex landscape model (input/output data communication between individual models);
- **input data requirements of the models** – (needs) - *a)* quantitative data organized within global coverage of landscape units which are homogenous as for topography, soil, climate and management is essential to run the EPIC model (for more information on EPIC model data requirements see the APPENDIX 1), *b)* statistical data for selected statistical units (country-level administrative units further stratified by topography and soil) on area portion of land cover/land use categories and/or average values of environmental indicators coming from EPIC modeling are required by the FASOM model;
- **global data availability and quality** – (limits) - *a)* thematic data is of various origin: geographic data directly based on earth observations (interpreted/non-interpreted), digital thematic maps, census data and other geographical data coming from complex interpretations or modeling, *b)* data quality varies significantly across the available data: spatial, attribute and temporal resolution of the data, its thematic relevance and general accuracy and reliability, *c)* data accuracy and reliability may decrease after necessary

estimations of missing data based on existing data and/or expert knowledge is done, *d)* simplifications of general modeling concept due to the missing data without the possibility of its estimation from existing data sources is necessary;

- **data harmonization** – (limits) - common spatial reference and spatial resolution have to be set for the data of different source and quality and different way of the data spatial referencing (geo-referencing or geo-coding) to the common spatial reference may lead to loose of information.

2. Primary data identification – inputs for the global database

The list of the data sources given below is a result of internet and literature search conducted under the first stages of the GEO-BENE project. The aim of this was to gather the information on the best data available globally which could satisfy the model (and modeling) requirements (for more particular information on EPIC model data requirements see the APPENDIX 1). All of the data sources listed below were directly used for compiling the global database; identification and description of other data sources without such relation to global database would go beyond the scope of this report.

The final input data selection for models (and modeling) followed an assumption of the data sources used for global database should represent a sample of data available from public domains and any special contracts or other restrictions except the copyright or easy-to-get licenses are not needed to get and use the data. Most of data can be directly downloaded in digital form using on-line mapping and downloading services; some of the data have to be requested from the data authorities, whereas some others represent only a hardcopy publications.

Categorization of the data sources we introduce here should emphasize the differences in the way of the data acquisition (data gathering and data processing methods, mapping methods) for this could have significant influence on the quality and accuracy of the information coming from the data interpretations as well as it can better indicate what global earth observation data are up to hand for the SBA agriculture data-model fusion based modeling.

2.1. Global earth observations based digital data

This group represents the data coming directly from earth observation systems and earth observation data only slightly processed or interpreted. Data is originally in raster format with various spatial resolutions (e.g. space or air-born observations) or in form of to single or multi- point related measurements (e.g. weather station data).

2.1.1. Digital elevation data (SRTM, GTOPO30)

The high-resolution global Shuttle Radar Topography Mission digital elevation model (further referred as SRTM) derived by NASA (http://www2.jpl.nasa.gov/srtm/) was used as a source of global elevation data. SRTM digital elevation model is available in 3’’ horizontal resolution (approximately 90 m at the equator) for areas between the latitudes from 60 N to 60 S, the altitude measure units are meters above a sea level.

Global 30 Arc Second Elevation Data (further referred as GTOPO30) (http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html*)* was used as a source of global elevation data. GTOPO30 is a global digital elevation model available in 30’’ horizontal resolution (approximately 1 km at the equator); the altitude measure units are meters above a sea level. It was derived from several raster and vector sources of measured and pre-processed topographic information. GTOPO30, completed in late 1996, was developed over a three year period through a collaborative effort led by staff at the U.S. Geological Survey's EROS Data Center.

2.1.2. Land cover data (GLC2000)

The Global Land Cover for year 2000 (http://www.gvm.jrc.it/glc2000/defaultGLC2000.htm) produced as a common activity of several national and international institutions coordinated by JRC (further referred as GLC2000) was used as a basic source of land cover information at global scale. GLC2000 global raster is available in spatial resolution of approximately 32’’ (approximately 1 km at the equator). Information on spatial distribution of 21 land cover classes interpreted from SPOT 4 VEGETATION 1 program satellite imagery (http://www.cnes.fr/web/1468-vegetation.php) using Land Cover Classification System of FAO (Di Gregorio et Jansen 2000) is available from GLC2000 legend (Table 2.1).

Table 2.1: *Legend to Global Land Cover 2000 (GLC2000)*

LAND COVER CLASS	CLASS DESCRIPTION
1	Tree Cover, broadleaved, evergreen
2	Tree Cover, broadleaved, deciduous, closed
3	Tree Cover, broadleaved, deciduous, open
4	Tree Cover, needle-leaved, evergreen
5	Tree Cover, needle-leaved, deciduous
6	Tree Cover, mixed leaf type
7	Tree Cover, regularly flooded, fresh water
8	Tree Cover, regularly flooded, saline water
9	Mosaic: Tree Cover / Other natural vegetation
10	Tree Cover, burnt
11	Shrub Cover, closed-open, evergreen
12	Shrub Cover, closed-open, deciduous
13	Herbaceous Cover, closed-open
14	Sparse herbaceous or sparse shrub cover
15	Regularly flooded shrub and/or herbaceous cover
16	Cultivated and managed areas
17	Mosaic: Cropland / Tree Cover / Other natural vegetation
18	Mosaic: Cropland / Shrub and/or grass cover
19	Bare Areas
20	Water Bodies
21	Snow and Ice
22	Artificial surfaces and associated areas
23	No data

2.1.3. Weather data (ECWMF)

The European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom provides an integrated weather forecasting system based on of processing manifold earth observation data (http://www.ecmwf.int/products/). Grid of 2.5°spatial resolution data on daily weather (further referred as ECWMF) was used to calculate monthly statistics required by EPIC weather generator.

2.2. Digital thematic maps

This group represents digital versions of hardcopy maps created by classical mapping methodologies or other digital thematic maps which has not been directly processed on the basis of global earth observations data. Data is originally available in vector format (polygon or polyline data).

2.2.1. Administrative regions (GAUL)

Global Administrative Regions Layer version 2007 () (http://www.fao.org/geonetwork/srv/en/metadata.show?id=12691&currTab=simple, further referred as GAUL) processed under the authority of the FAO and European Commission was used as a source of the country-level administrative regions data. Countries are in GAUL vector layer identified both by country name and country code which can be easily compared with official United Nations coding list of countries and world regions (http://unstats.un.org/unsd/methods/m49/m49.htm).

2.2.2. Soil data (DSMW)

The digital version of the 1:5 000 000 scale Soil map of the world (further referred as DSMW) version 3.6 (http://www.fao.org/geonetwork/srv/en/metadata.show?id=14116&currTab=simple) was used as a source of data on distribution of major soil units across the world. DSMW soil mapping units delineations (available both in vector or 5 arc minutes resolution raster) are attributed with information on soil mapping unit soil components (soil typological units and soil phases) and information on their area portion (%) of the soil mapping unit delineation. Totally, information on 106 soil typological units classified according to map legend (FAO-UNESCO 1974) and 5 miscellaneous non-soil units (glaciers, inland waters, dune and shifting sands, rock debris and outcrops, salt flats) can be retrieved from the map.

2.3. Census and other non-spatial data

This data group represents mostly the statistical data related (geo-coded) to statistical administrative units (country and first sub-country). Some of the data is a result of a slight interpretation or aggregation of original statistics. Data is originally digital attribute data organized in the tables; some data is in form of hardcopy publications (plain text, tables).

2.3.1. Agricultural statistics (FAOSTAT, FAOAQUASTAT, IFA)

FAO on-line data server (further referred as FAOSTAT) provides vide range of country specific agricultural statistics. FAOSTAT served a source of 1961 to 2006 years country-level statistics on crop harvested areas (http://faostat.fao.org/site/ 567/default.aspx) and 2002 to 2005 years statistics on total consumption of nutrients (N, P_2O_5, K_2O) for selected countries (http://faostat.fao.org/site/575/default.aspx).

Website AQUASTAT maintained by FAO (further referred as FAOAQUASTAT) provides specific information on water management in agriculture, including irrigation areas statistics and water withdrawal by agriculture statistics. Country and crop specific irrigation calendar for the 90 countries of the world was used for global database as the source information on start and end days of crop planting and harvesting (http://www.fao.org/nr/water/aquastat/main/index.stm).

International Fertilizer Industry Association provides statistics on country and crop specific fertilizer consumptions (further referred as IFA). IFA dataset (http://www.fertilizer.org /ifa/statistics.asp) was used as a source of data on crop and country specific fertilizer application rates and total country-level average nutrients consumption (N, P_2O_5, K_2O).

2.3.2. Crop calendar data and documents (USDA, MARS, Crop and Country calendars)

Climate and crop calendar for the key producing regions and countries is available from U.S. Department of Agriculture document (USDA 1994, further referred as USDA). In the publication concentration zones of major crops for each country are identified and completed with information on historical averages of crop area (ha), yields (t/ha) and production (t). Coarse grain, winter and spring wheat, barley, rice, major oilseeds, sugar crops and cotton are included in USDA publication.

Crop calendars, agriculture practices calendars, crop rotations and other information on selected crops for the part of Europe (Estonia, Latvia, Lithuania, Poland, Czech Republic, Slovakia, Hungary, Slovenia, Romania, Bulgaria and Turkey) are available from publications of Kučera et Genovese 2004a, 2004b, and 2004c (further referred as MARS dataset). Wheat, barley, maize, rice, sugar beet, sunflower, soya bean, rape, potato, cotton and olive for Italy, Spain and Greece are given by Narciso et al. (1992). Some other sources of national crop calendar data used for global database are listed in APPENDIX 2.

Crop harvest calendars for sugar beet (FAO, 1959a), sugarcane (FAO, 1959b) and coffee (FAO, 1959c) include selected countries of the world. Rice crop calendar (http://www.irri.org/science/ricestat/) contains the data on planting and harvest dates (months) of rice for selected countries of the world. The crop calendar (planting and harvesting dates) of winter and spring wheat for Albania, Austria, Bulgaria, Czech Republic, Finland, Hungary, Norway, Poland, Romania, Slovak Republic, Sweden, Switzerland, Ex-Yugoslavia is available from publication of Russell et Wilson (1994). Autumn or winter and spring barley crop calendar (planting and harvesting dates) for Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain and United Kingdom is available in publication of Russell (1990)

The potato crop calendar (MacKerron 1992) includes dates of planting and harvesting (decade and month) for Germany, France, Italy, Netherlands, Belgium, United Kingdom, Ireland, Denmark, Greece, Spain and Portugal. Information about potato and sweet potato cultivation with emphasis on developing countries collects International Potato Centre. On their web-site are presented the potato crop calendar for countries of Africa, South and Middle America and Eurasia (http://research.cip.cgiar.org/confluence/ display/wpa/Home). The crop calendar of sweet potato is available for the countries of Africa and Asia (http://research.cip.cgiar.org/confluence/display/WSA/Home).

2.4. Interpreted data or modeling outputs

This group represents the data coming from various interpretations based on existing data and expert knowledge or data coming from modeling (interpolations results, statistical down-scaling results, etc.). Such a data represents secondary data not directly measured or collected. The interpretation methodologies used for data creation influence significantly the data accuracy and reliability. Various digital geo-referenced or geo-coded data available in this group have various spatial resolutions and is available in raster or vector representation depending on the data origin.

2.4.1. Soil data (WISE)

International Soil Reference and Information Centre (ISRIC) 5 by 5‘ grid of soil properties estimation based on global soil distribution (DSMW) and soil profile data (WISE soil profile database, http://www.isric.org/UK/About+Soils/Soil+data/Geographic+data/Global/Global+soil+profile+data.htm) interpretation (further referred as WISE, http://www.isric.org/UK/About+Soils/Soil+data/Geographic+data/Global/WISE5by5minutes.htm) was used as a source of DSMW soil typological unit specific data on soil analytical properties for 5 depth intervals of soil profile (20 cm intervals for total depth of 1m). Detailed interpretation methodology for WISE compilation is described in publication of Batjes (2006).

2.4.2. Land use and land management data (GLU, Manure data)

Global crop distribution data processed by International Food Policy Research Institute was used as a source of basic information on land cover and land use. The data (further referred as GLU) represents a global coverage of a regular-shaped statistical units (5' spatial resolution grid) attributed with estimated crop cultivation and harvest areas (physical area in ha) and crop production (tons/ha) for 20 globally most important crops or crop groups (wheat, rice, maize, barley, millet, sorghum, potatoes, sweat potatoes and yams, cassava, bananas and plantains, soybean, other pulses, sugar cane, sugar beet, coffee, cotton, other fiber crops, groundnuts, other oil crops). Estimations are done separately for the four agricultural production systems (high input - irrigated, high input - rainfed, low input - rainfed and subsistence management systems). Final dataset resulted from downscaling of many national and sub-national agricultural census data using additional spatial information on land cover (GLC2000), crop suitability and management system potential yields (agro-ecological zones assessment data, Fischer et al. 2000), irrigation areas (Global irrigation map, Siebert et al, 2007) and population density data (Gridded Population of the World, http://sedac.ciesin.columbia.edu/gpw/index.jsp). All the methodological details are given in the publication of You et Wood (2006). Actually, GLU dataset is not available for download by any public on-line service. For global database GLU data set was provided by IFPRI after personal communication with Dr. Liangzhi You.

Global scale 5' spatial resolution on nitrogen rates coming from manure application (further referred as manure data) compiled by Liu et al. (in press) were used as a source dataset on nitrogen fertilization and total manure application. Manure data was interpreted from global data on livestock density (Gridded Livestock of the World, http://www.fao.org/ag/AGAinfo/resources/en/glw/default.html) developed by FAO in collaboration with the Environmental Research Group Oxford and FAOSTAT data on country and livestock specific data on slaughter weights using published knowledge on nitrogen rates in livestock excretion and amounts of manure recycled to cropland. Actually, manure dataset is not available for download by any public on-line service. For global database the dataset was provided after personal communication with Dr. Junguo Liu.

2.4.3. Weather data (Tyndall)

The Tyndall Centre for Climate Change Research of University of East Anglia, Norwich, UK provides data on historical time series of global weather for the period from 1901 – 2000 and 16 climate change scenarios (further referred as Tyndall, http://www.cru.uea.ac.uk /~timm/grid/TYN_SC_2_0.html). Global scale land surface coverage 0.5°spatial resolution grids of modeled climate data on cloud cover, diurnal temperature range, precipitation, temperature, vapor pressure were compiled from several interpolated global and regional climate datasets. Methodological details of Tyndall data are described in publication of Mitchel et al. (2004).

3. Reference for geographical representation of the data

Three-level hierarchical system of geographical objects was designed for spatial referencing the global database data on natural and management landscape characteristics. It comprises primary geographical reference grid (chapter 3.1), secondary geographical reference objects (HRU, 30’ spatial resolution grid and country-level administrative unit, chapter 3.2) and tertiary reference objects (landscape units, chapter 3.3). Database reference objects (simulation units, chapter 3.3) provide the least non-spatial data reference in the global database.

3.1. Primary geographical reference grid

Primary geographic reference is the basic spatial frame for geographical representation and visualization of all the data stored in global database. It is a basis for spatial referencing of secondary and tertiary reference objects. Moreover, primary geographic reference is the basic harmonization tool for the geographical data coming from various sources.

<u>*3.1.1. 5’ spatial resolution geographical grid (Global grid)*</u>

Global extent (-90° S to 90° N and -180° W to 180° E) grid designed in geographical coordinate system WGS 84 with pixel resolution of 5’ (about 10 X 10 km on equator) was created to serve the primary geographical reference for the global database (further referred as global grid). Land surface mask was used to keep only those pixels of global grid which represent land surface (any other pixels representing oceans are not relevant for global modeling). Land surface mask resulted from intersection of the land surface subsets of the most significant geographical data inputs (GTOPO30, SRTM, DSMW, GLC2000, GAUL, IFPRI-GLU) harmonized in global grid (chapter 3.2.). Decision was done also to exclude Antarctica from global grid due to the most of its area is covered by ice or bare rocks. Totally, global grid comprises 2.186.775 pixels.

Each grid cell of the global grid is indexed by column and row number counted from upper left corner of the grid (point coordinates 90° N, -180° W). Column numbers ranges from 1 to 4320, row numbers ranges from 1 to 2160. Independently from column-row indexing each pixel is indexed also by *x* and *y* coordinate (decimal degree) of pixel centroid. Point lattice can be then displayed via centroid coordinates to visualize global grid in a map. This makes global grid independent of a particular GIS platform used for compilation and storage of the data as well as it supports the exchange of geospatial data between various GIS or database systems via simple and highly interoperable ASCII text files (e.g. *txt*, *csv*). Classical database tools can be used for storage, maintenance and analyzing the data geo-referenced to point lattice and GIS support is needed only for displaying the data geographically in a map.

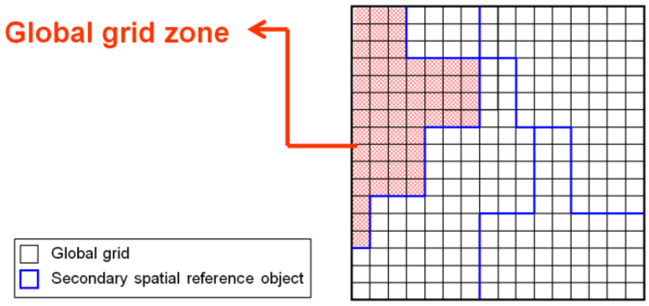
Modeling requires that all the data on area of spatial units is reported as real area values (e.g. ha or km^2). Real area (ha) for each pixel of global grid was calculated as a 1/36 of real area of corresponding 30’ resolution grid pixel (chapter 3.2.2). Real area of 30’ resolution grid resulted from transformation of the geographically not projected data (WGS84 coordinate system) into the equal area geographic projection system (Goode-Homolosine projection) following the routine described by Lethcoe and Klaver (1998).

3.2. Secondary geographic reference

Secondary geographic reference objects provide spatial reference for all the data direct referencing of which to the global grid is not advantageous or possible (chapter 3.2.2, 3.2.3) Secondary reference object also serve as data stratification tool in bio-physical and optimization models communication (chapter 3.2.1). Along with referencing function secondary spatial reference objects play important role in the delineation of landscape units (chapter 3.3., Fig. 3.2).

Particular secondary geographic reference object is spatially referenced to global grid as an attribute value assigned to relevant pixel or group of pixels. It can be geographically displayed on a map as a spatial zone of global grid (Fig. 3.1).

Fig. 3.1: *Secondary geographical reference object zone (e.g. HRU) visualized via global grid.*



<u>*3.2.1. Homogenous response units (HRU)*</u>

Concept of homogenous response units (HRU) used here was adopted after slight modification from earlier works (Schmid et al. 2006, Balkovič et al. 2006, Stolbovoy et al. 2007) as a general concept for delineation of basic spatial units. Only those characteristics of landscape, which are relatively stable over time (even under climate change) and hardly adjustable by farmers, were selected. HRU is a basic spatial frame for implementation of climate-change and land management alternative scenarios into global modeling and therefore it is one of basic inputs for delineation of landscape units (chapter 3.4, Fig. 3.4). Moreover, HRU provides a possible interface for communication of bio-physical and optimization models (EPIC model derived and consecutively HRU level aggregated information on environmental indicators can input FASOM optimization modeling).

Tab. 3.2: *Altitude, slope and soil class criteria for HRU delineation*

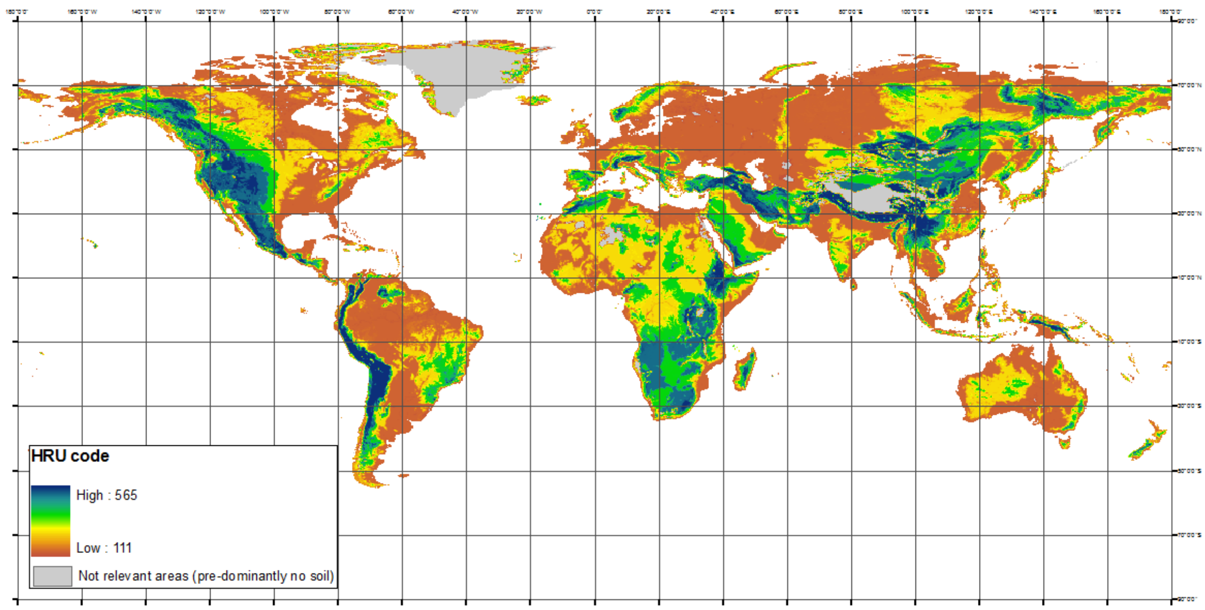
LAND CHAR.	UNIT	CLASS (CLASS INTERVAL)
altitude	meters	**1** (*0 – 300*), **2** (*300 – 600*), **3** (*600 – 1100*), **4** (*1100 – 2500*), **5** (*> 2500*),
slope inclination	degree	**1** (*0 – 3*), **2** (*3 – 6*), **3** (*6 – 10*), **4** (*10 – 15*), **5** (*15 – 30*), **6** (*30 – 50*), **7** (*> 50*)
soil	-	**1** (*sandy*), **2** (*loamy*), **3** (*clay*), **4** (*stony*), **5** (*peat*), **88** (*no-soil*)

HRU is spatially delineated as a zone of global grid having same class of altitude, slope and soil (HRU class definitions are listed in Tab. 3.2.):

- Dominant altitude class was calculated by raster algebra as a zonal majority value of pre-classified GTOPO30 raster altitude class over a one global grid pixel area;

- Dominant slope class was calculated by raster algebra as a zonal majority value of pre-classified 30'' spatial resolution temporary raster slope class over a one global grid pixel area. Temporary raster used for calculations was interpreted from original SRTM and GTOPO30 data as follows. The SRTM data calculated slopes at 3" spatial resolution were grouped into the classes 0°- 3°, 3°-6°, 6°-10°, 10°-15°, 15°-30°, 30°-50° and >50°. For the 30" resolution raster zonal majority procedure was done to get the 60 N to 60 S extent raster of slope classes. To fill up the missing regions from 60°N to 90°N and 60°S to 90°S a slope raster with the GTOPO30 was calculated. The region 60°N to 60°S was covered by both SRTM and GTOPO30 derived slope data. This overlapping region was used to create a look-up table which allowed transforming the slope from the GTOPO30 to the slope class shares of the SRTM and fill up the missing regions.
- Dominant soil class represents most frequent soil class of DSMW soil mapping unit (as for its relative area) assigned to global grid pixel by intersection (spatial join) of global grid centroid lattice and original DSMW layer. Soil typological units of the particular DSMW soil mapping unit were classified into five pre-defined soil classes. Based on WISE soil profile data on aggregated soil texture classes (coarse, medium and heavy texture) sandy, loamy and clay soil classes were interpreted; soil typological units classification was applied for stony and peat soil classes interpretation. An arbitrary value of 88 was assigned to all non-soil bodies. Sum of the areas of all soil typological units classified to the same soil class or sum of areas of all non-soil bodies having dominant area portion of the total DSMW mapping unit area was then applied as a criterion for global grid pixel dominant soil class.

Fig. 3.2: *Global HRU coverage*.



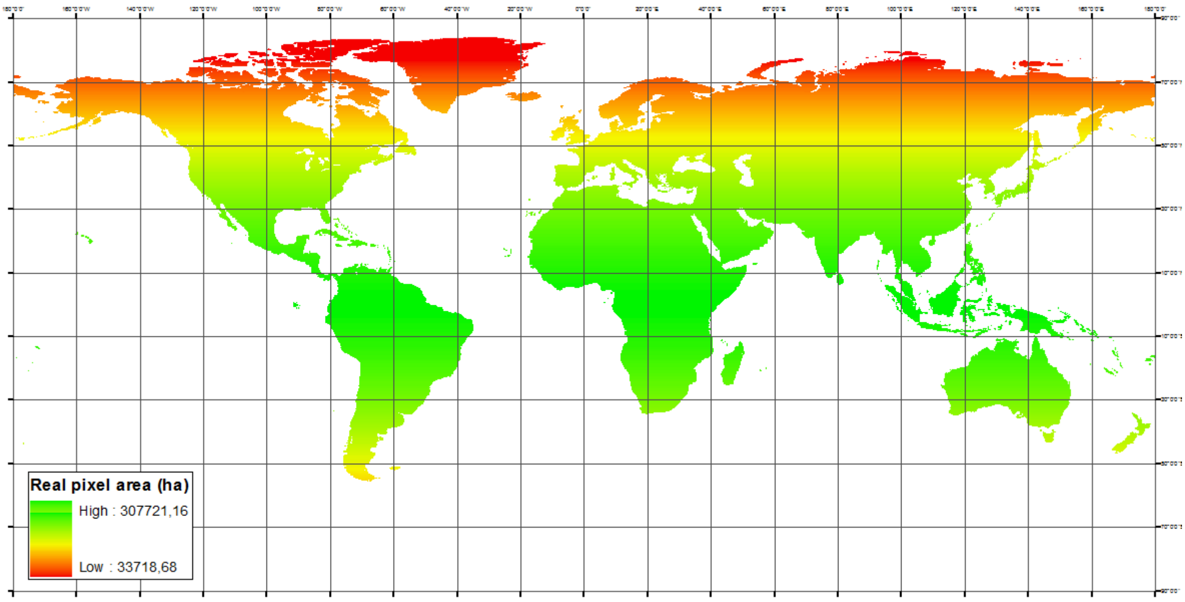
Altitude, slope and soil class value assigned to 5' spatial resolution pixel represents spatially most frequent class value (not average!) taken from input data of higher spatial (GTOPO30, SRTM) or attribute (DSMW) resolution than target dataset (i.e. idea of "the most likely" natural conditions is adopted here). This implies that not absolute information on landscape quality and variability over the 5' spatial resolution pixel area is transferred to global grid in data harmonization process and resulting harmonized information used for HRU delineation is just broad approximation to real variability of the global landscapes.

Totally, 150 unique combinations of altitude, slope and soil class resulted from HRU delineation process (Fig. 3.2). Each delineated HRU zone is indexed by numerical code assembled from code of altitude, slope and soil on first, second and third position, respectively.

3.2.2. 30' spatial resolution geographical grid (PX30)

Overlay of global grid and global extent (-90° S to 90° N and -180° W to 180° E) 30' spatial resolution grid (about 50 X 50 km on equator) designed in geographical coordinate system WGS 84 was done to get regularly-shaped zones of global grid indexed by column and row index of underlying 30' spatial resolution grid (column and row indexes counted from upper left corner, coordinates 90° N, -180° W). Each zone was also assigned with *x* and *y* coordinate values of corresponding 30' resolution pixel centroid.

Fig. 3.3: *Real area change with increasing latitude*



Real area (ha) of 30' resolution grid was calculated after transformation of the geographically not projected data (WGS84 coordinate system) into the equal area geographic projection system (Goode-Homolosine projection) following the routine described by Lethcoe and Klaver (1998). Real area (ha) change with latitude is shown on a map (Fig. 3.3).

30' resolution grid zone (further referred as PX30) provide a direct geographical reference for interpolated weather data (Tyndall) as well as it is an arbitrary spatial frame which is to secure local detail in geographical analyses and interpretation of the input data for bio-physical modeling (topography and soil data, land cover and land use statistics).

3.2.3. Administrative units (COUNTRY)

Simple overlay (spatial join) of GAUL data and the global grid centroid lattice was done to get country and first sub-country level administrative unit identification (country code) for all pixels of global grid. Consequently, original country-level administrative unit codes taken from original GAUL dataset were replaced by a country code from official UN country list. UN country codes from ad-hoc constructed look-up table (Tab. 3.1) were assigned to all administrative regions having no country information in GAUL dataset (geopolitically controversial administrative regions). Original GAUL coding was kept only for sub-country-level administrative regions.

Country level administrative regions (further referred as COUNTRY) provide a spatial reference for geo-coding the most of national-level agricultural census data and national or national level data on crop management calendars. Sub-country-level administrative regions provide an additional spatial reference for geo-coding the sub-national crop management calendar data for selected countries (chapter 4.3.3).

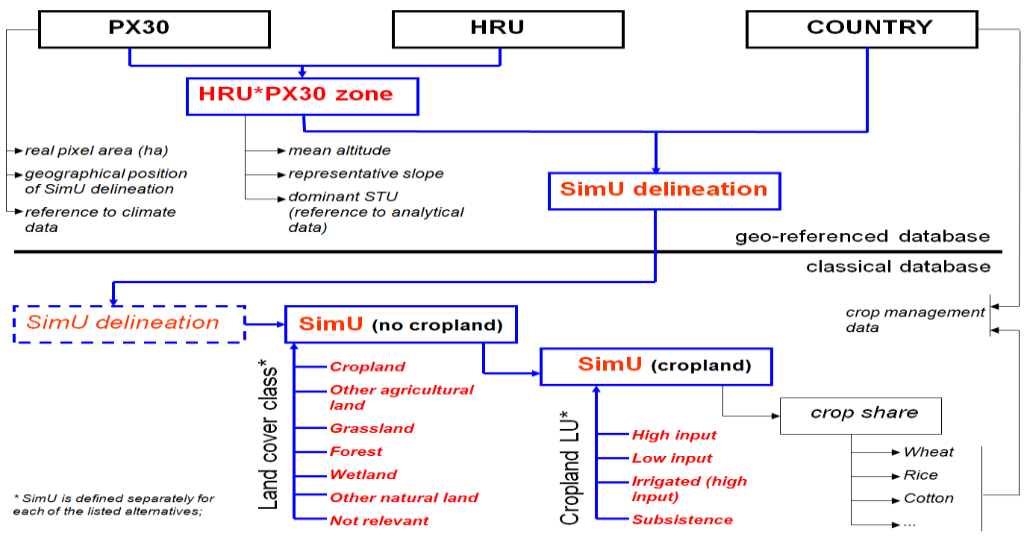
Tab. 3.1. *UN country codes for geopolitically controversial administrative regions.*

GAUL REGION (COUNTRY	UN COUNTRY CODE (COUNTRY NAME)
Aksai Chin	356 (India)
Arunashal Pradesh	356 (India)
Dhekelia and Akrotiri SBA	196 (Cyprus)
Gaza Strip	376 (Israel)
Hala'ib triangle	818 (Egypt)
China/India	156 (China)
Ilemi triangle	736 (Sudan)
Jammu Kashmir	356 (India)
Kuril islands	643 (Russian Federation)
Madeira Islands	620 (Portugal)
Ma'tan al-Sarra	736 (Sudan)
West Bank	376 (Israel)

3.3. Landscape units and simulation units

Landscape units and simulation units provide immediate reference for the global database data displaying in geographical or classical database. Simple scheme illustrating the definition and position of these units in global database is given in Fig. 3.4.

Fig. 3.4: *Landscape zones and simulation units – definition, functional position and referenced data*

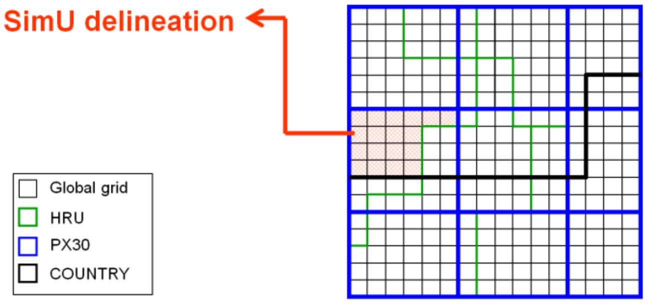


*3.3.1. Landscape units (HRU*PX30 zone, SimU delinetion)*

Landscape units were implemented to satisfy the bio-physical model requirements for spatial units being homogenous as for its natural conditions and landscape management. Landscape units are the smallest spatial units coming from intersect of HRU, PX30 and COUNTRY spatial delineations. The function of landscape units in global modeling is to provide both the immediate reference to the data required as inputs for bio-physical model (Fig. 3.4) and to provide the least possible spatial delineation (which can be further specified only on non-spatial level, chapter 3.3.2). Two hierarchical levels of landscape units are assumed in global modeling:

- **HRU*PX30** zone (Fig. 3.4.) is delineated as the smallest landscape body homogenous as for its natural conditions (topography, soil and weather). HRU*PX30 zone provides direct spatial reference for EPIC input data on soil and topography (average altitude, representative slope and soil typological unit specific analytical values);
- **Simulation unit delineation** (further referred as SimU delineation, Fig. 3.4, Fig. 3.5) is the HRU*PX30*COUNTRY zone delineated as the smallest landscape body homogenous as for its natural conditions (the same as above) but with further reference to a particular country-level administrative region. SimU delineation provides direct spatial reference for non spatial information on land cover and land use. Maximal area of SimU delineation is equal to an area of one 30' spatial resolution grid pixel and its area decrease from about 300 000 ha on equator to about 30 000 ha in high latitudes; minimal area of SimU delineation is equal to an area of one 5' spatial resolution grid pixel and its value decrease from about 8 500 ha on equator to about 950 ha in high latitudes.

Fig. 3.5: *SimU delineation visualized as a global grid zone.*



3.3.2. Simulation units (SimU)

Simulation unit (further referred as SimU) is non-spatial semantic unit which represents one of all possible land cover, land use (for cropland) and via this two also land management alternatives which can take place in the area defined by SimU delineation (Fig. 3.4.). In the global database SimU represent a unit which bears definite information on unique natural and management condition existing at particular place. This information is utilized in bio-physical modeling to assemble the set of management alternative specific input files for model runs. SimU provides also a reference for interpretation and displaying the bio-physical modeling outputs.

4. Input data interpretation for global database

4.1. Land cover and land use data

4.1.1. Land cover statistics

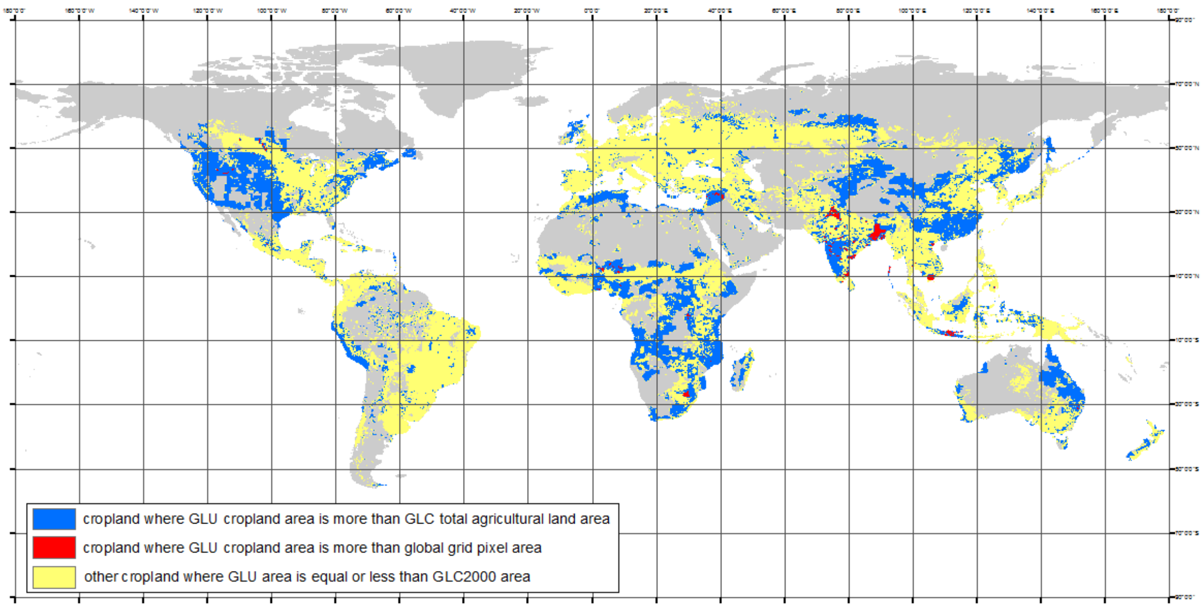
Combined GLC2000 and GLU datasets interpretation was done to get global grid and SimU delineation specific data on cropland area necessary for setting up the base-run scenarios for agro-ecosystem modeling (information absent in GLC2000) and data on other land cover classes area (grasslands, forests, wetlands, other natural vegetation) necessary for land cover/land use optimization modeling (information absent in GLU).

Table 4.1: *GLC2000 classes derived global database land cover classes*

GLOBAL DATABASE LAND COVER CLASS	ORIGINAL GLC2000 CLASSESS (Tab. 2.1)
total agricultural land	16,17,18
grassland	13,
forest	1, 2, 3, 4, 5, 6, 9, 10
wetlands	7, 8, 15
other natural vegetation	11, 12, 14
not relevant land covers	19, 20, 21, 22

Zonal analyze of pre-classified GLC2000 layer (Tab. 4.1.) over the global grid was done to get pixel specific statistics on total cropland, grassland, forest, wetland, other natural vegetation and not relevant land cover classes real areas (ha). Pixel specific cropland area (ha) was calculated from original GLU data by summing up all particular crop areas over all assumed management systems. Consistence of GLU and GLC2000 data was checked by subtracting GLU derived cropland area from GLC2000 derived total cropland area. Result of the consistence check is shown on a map (Fig. 4.1).

Fig. 4.1: *GLU and GLC2000 land cover data inconsistence.*



There is lot of pixels having GLU cropland area higher than GLC2000 total agriculture area; even pixels having higher GLU cropland area than total pixel area were identified in dataset. Reason for that resides in an inconsistence of GLC2000 and national agricultural census data (more agricultural land is reported in census than it is available in GLC2000) as well as in GLU model total area of all pixels was arbitrary set to 9000 ha which have could caused some of the inconsistencies (personal communication with Dr. Liangzhi You).

It was decided that GLU cropland area should be secured in final harmonized land cover dataset (cropland land cover class) with only exception in the case of GLU cropland area is higher than total pixel area; and data on all other land cover classes were adjusted following several simple rules:

- if the GLU derived cropland area was less than GLC2000 derived total agricultural land area an additional land cover class (other agricultural land) was introduced and assigned with area value calculated as a difference of GLC2000 total agricultural land area and GLU cropland area, GLC2000 derived areas of all other land cover classes were kept;
- if the GLU derived cropland area was more than GLC2000 derived total agricultural land area additional land cover class (other agricultural land) was given by zero value and areas of all other land cover classes were recalculated based on their area portion of global grid pixel so that resulting sum of their areas was equal to difference of total pixel area and GLU reported cropland area;
- if the GLU derived cropland area was more than total pixel area; cropland area value was arbitrary set to total pixel area and areas of all other land cover classes were set to zero.

For each pixel of global grid a metadata field was created to indicate the method used for land cover data harmonization. Finally, harmonized land cover dataset was spatially aggregated by zonal sum of all land cover classes over the SimU delineation zone to get SimU delineation specific data on land cover.

4.1.2. Land use statistics

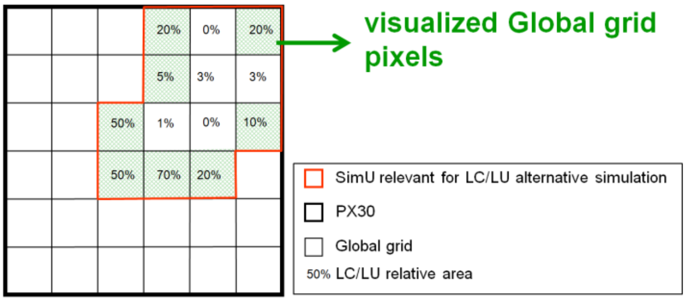
Information on cropland land use classes (chapter 2.4.2) is available from GLU dataset. Pixel specific cropland management system area (ha) was calculated from original GLU data by summing up all crop areas over particular management system. Additional area adjustments based on management system area portion of total cropland were done in case of GLU dataset derived specific cropland area was different from cropland area of harmonized land cover dataset. Finally, spatial aggregation of land use dataset was done by zonal sum of all land use classes over the SimU delineation zones to get SimU delineation specific data on land use.

4.1.3. Land cover/land use relevance and visulisation mask

An arbitrary 5% threshold of land cover area portion of total SimU delineation area was set to tell whether SimU delineation is relevant or not for simulation of the defined land cover alternative (i.e. which SimU are to be defined across the SimU delineation area). Similarly, a relevance of cropland land use alternative for simulation was set based on 5%

threshold of cropland management system area portion of total cropland area. Relevance masks were set for to limit bio-physical model runs only to most representative management alternatives across the SimU delineation area. Relevance masks are not mutually exclusive and in a case it meets the threshold more than one land cover/land use alternative can be assumed for the SimU delineation. Absolute SimU delineation relevance mask based on spatial dominance of particular cropland management system across the cropland was in addition set only for cropland land use alternatives (chapter 4.3.2).

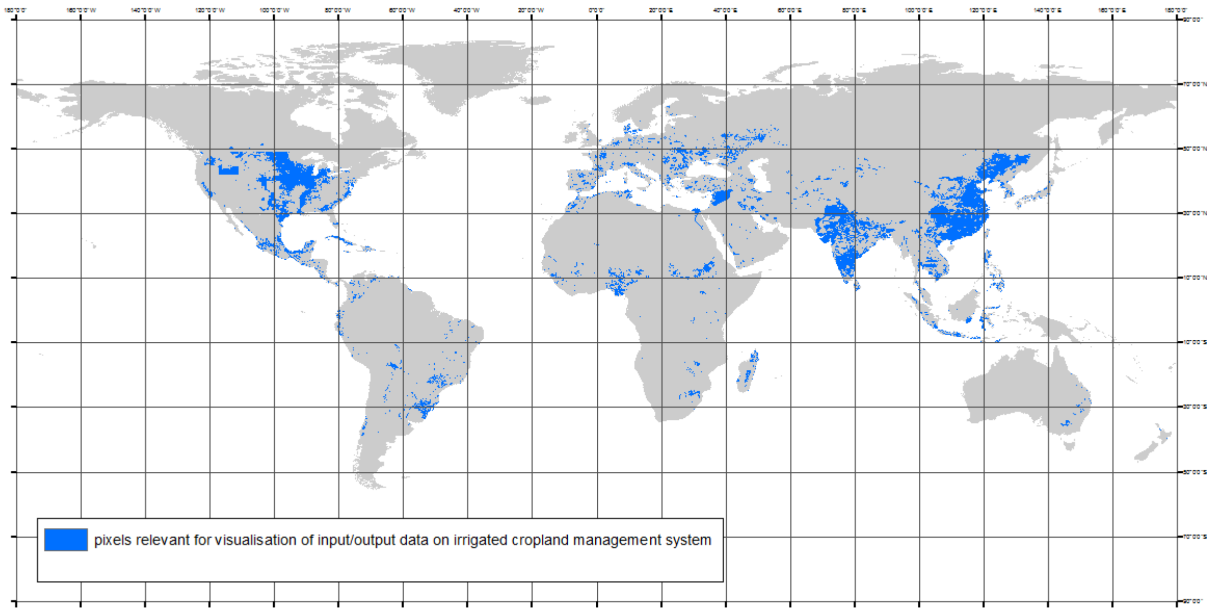
Fig. 4.1: V*isualization mask for land cover (land use) data*



SimU delineation is the least spatial object which can be visualized on the map and all related information on land cover/land use is organized only as a non-spatial statistics (chapter 3.4.). To overcome this problem, for visualization of the SimU specific data (input/output data for bio-physical model, management alternatives spatial pattern, etc.) a visualization mask was defined for each of the global grid pixels.

If a particular land cover/land use alternative is considered for visualization, only those pixels of global grid are visualized which represents relevant SimU delineation zone and which meet the 5% threshold of minimum land cover area portion of total pixel area or land use area portion of total cropland area in particular pixel (Fig. 4.1, Fig. 4.2).

Fig. 4.2: *Land cover/land use visualization mask – example of irrigated cropland management system.*



4.2. Topography and soil data

4.2.1. Topography data

Zonal mean of altitude value (m) coming from GTOPO30 was calculated over the HRU*PX30 zone to get average altitude as an input for bio-physical model (Fig. 4.3.).

Fig. 4.3: *Global pattern of HRU*PX30 zone average altitude.*

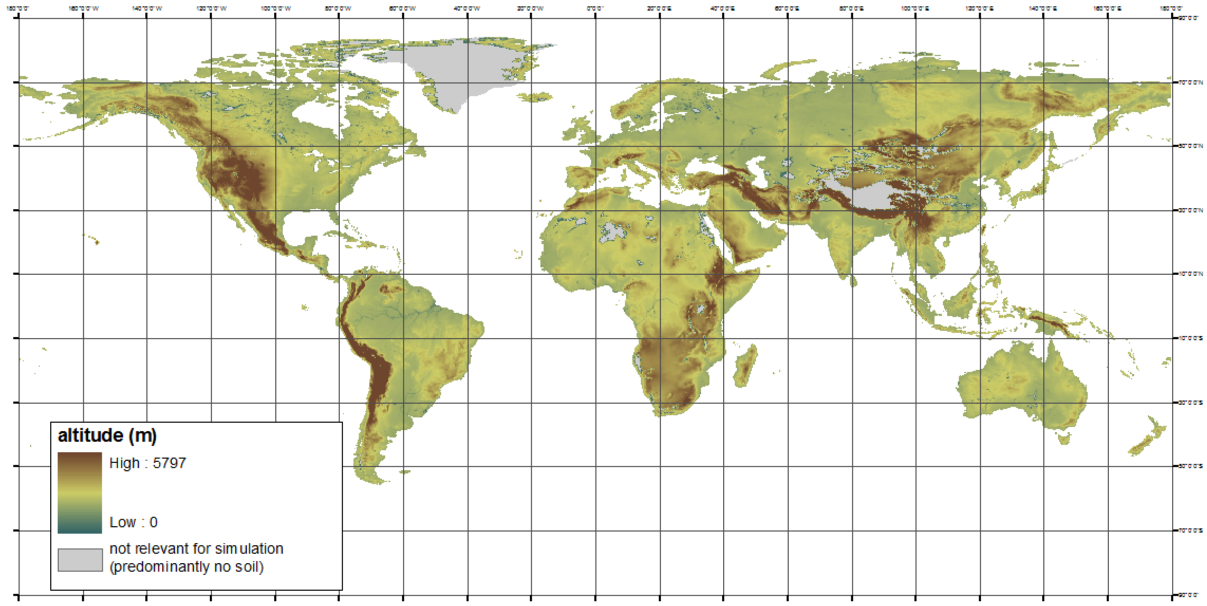
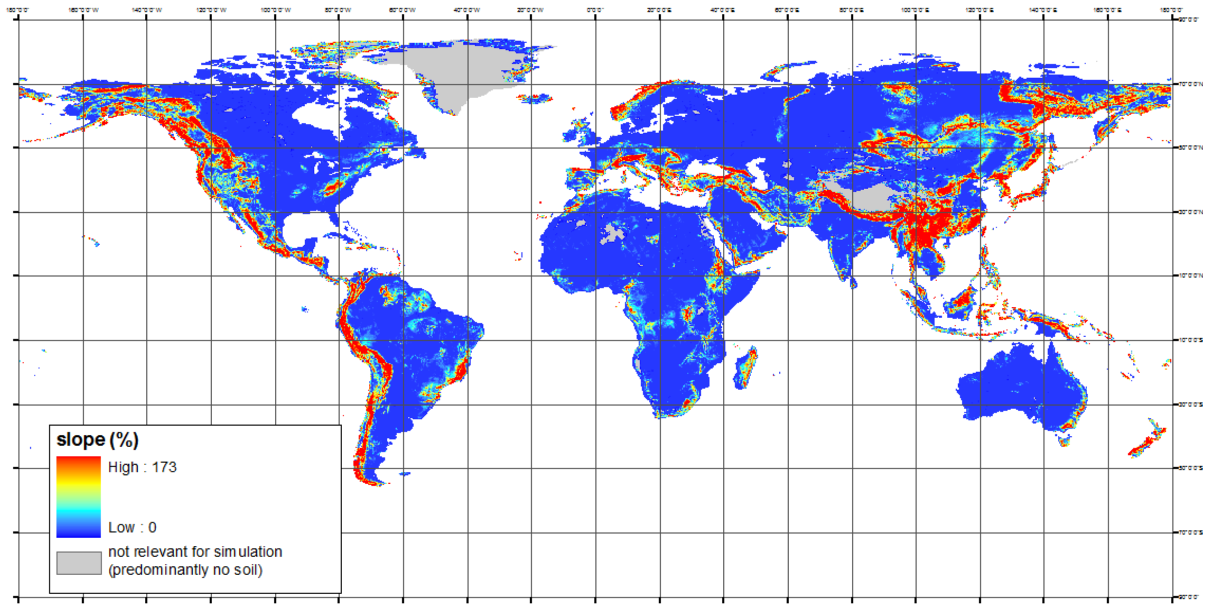


Fig. 4.4: *Global pattern of HRU*PX30 zone representative slope.*



Representative slope value for slope class coming from HRU (Tab. 4.2) was assigned to HRU*PX30 zone after recalculation to percent by simple equation (*slope in % = tg(slope in deg) * 100*) to get slope value required by bio-physical model (Fig. 4.4). Dominant slope class interval method derived representative value seems to be more appropriate as an average value for the averaging of slope over the HRU*PX30 zone could result in non-realistic (artificial) values in a case of wide range of slopes is presented within a zone.

Table4.2: *Representative slope values assigned to the slope classes*

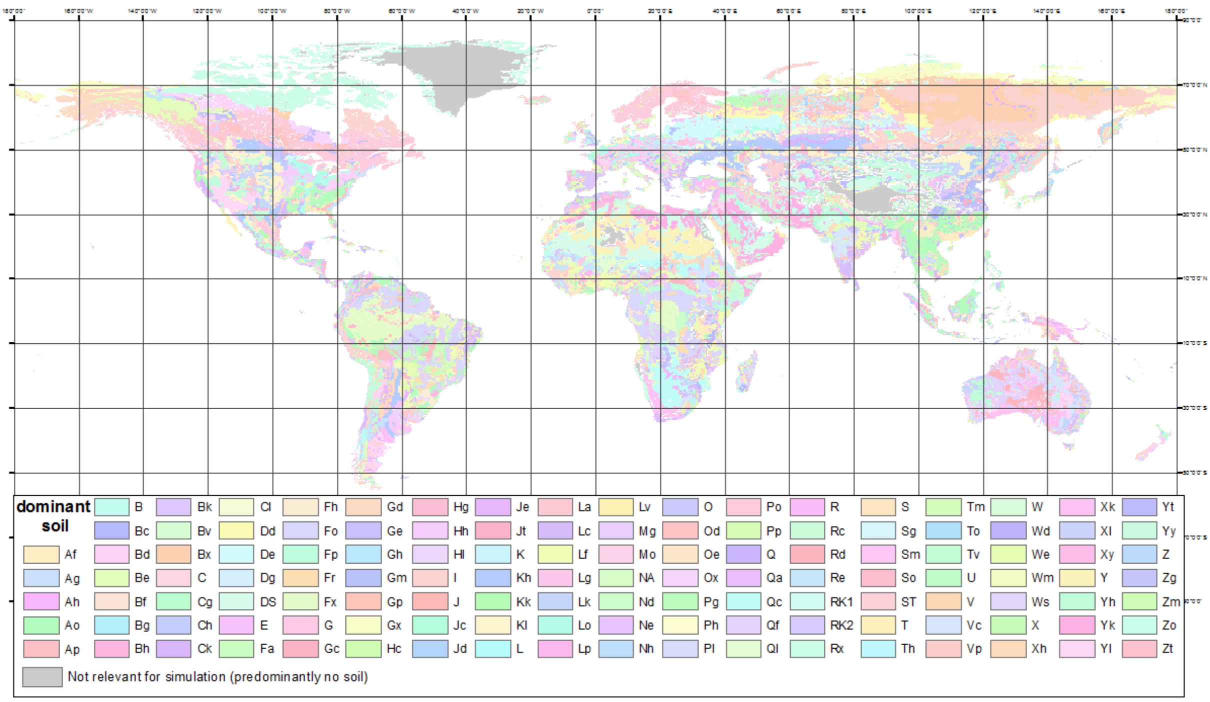
HRU SLOPE CLASS INTERVAL	REPRESENTATIVE SLOPE VALUE (DEG)
0 - 3	1
3 - 6	4
6 - 10	8
10 - 15	12
15 - 30	23
30 - 50	40
> 50	60

PX30 pixel centroid *x* and *y* coordinate values were assigned to all corresponding HRU*PX30 zones as a representative value of landscape unit geographical position required by bio-physical model. This simplification should not affect negatively the simulations.

4.2.2. Analytical characteristics of soil

Data on analytical characteristics of soil required by bio-physical model are to HRU*PX30 zone related via information on dominant soil typological unit. A slightly modified methodology firstly introduced by Batjes at al. (1995) for DSMW data interpretation was applied to get HRU*PX30 dominant soil typological unit from DSMW data.

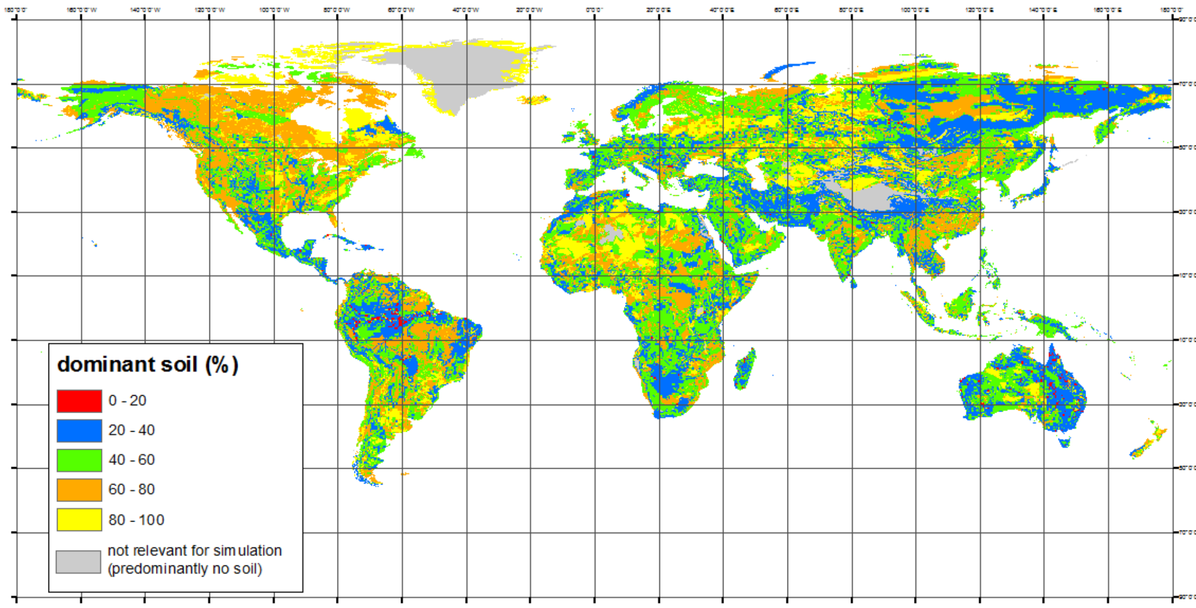
Fig. 4.5: *Global pattern of HRU*PX30 zone dominant soil typological units (soils according to FAO-UNESCO 1974), RK1, RK2, DS, and ST stands for no soil bodies, NA for non-identified soil bodies.*



Area percentage of each DSMW soil mapping unit identified within the particular HRU*PX30 zone extent was calculated in the first step using the soil mapping unit data obtained from from intersect of global grid centroid lattice and original DSMW layer. In the next step, soil typological unit specific relative areas (%) calculated from data on DSMW soil mapping unit area percentage and data on DSMW soil mapping unit composition (chapter 2.2.2) were summed over the HRU*PX30 zone to get total area portion (%) for each of the soil typological units. Soil typological unit of the highest area portion was selected as dominant one for HRU*PX30 zone (Fig. 4.5).

Dominant soil typological unit relative area varies from 14 to 100% across the global coverage of HRU*PX30 zones (Fig. 4.6.). This implies that in areas with high diversity of soils (the case of dominant soil typological unit area is less than 60%) dominant soil typological unit based concept cannot be considered more than just a broad approximation to the appropriate model of soil variability.

Fig. 4.6: *Area percentage of dominant soil typological unit of HRU*PX30 zone.*



The most of the soil analytical data required by bio-physical model was adopted directly from WISE dataset without or with only slight modifications such as transformation of measurement units or re-calculation of relative to absolute values. Some other soil analytical parameters (hydrological soil group and soil hydrological parameters, albedo of moist soil) missing in WISE dataset were estimated from WISE data by available methodologies or published knowledge.

Hydrological soil group was interpreted for each soil typological unit from WISE analytical data on soil texture by simplified rules from official USDA-NRCS engineering manual (USDA-NRCS 2007). Soil typological unit specific hydro-physical characteristics were estimated from WISE analytical data on soil texture and bulk density by combined methodology. Neural-network algorithm based pedo-transfer model Rosetta (Shaap et Bouten 1996) produced saturated hydraulic conductivity value and soil hydrological parameters necessary for calculation of soil water content at field water capacity and wilting point by Van Genuchten equation (Wösten et Van Genuchten 1988). An arbitrary value of 0,15 was assigned to all soil typological units as albedo of moist soil representing median of the 0.1 – 0.2 albedo interval for dark soil surfaces given by Dobos (2006).

All salt flats and shifting sands no-soil bodies (ST, DS) and all non identified soil bodies (NA) which resulted from HRU*PX30 zone dominant soil typological unit analyze were assigned by analytical values of other available soil typological units after the WISE dataset rules (Batjes 2006). In a case of rock non-soil bodies (RK1, RK2) were identified as dominant soil typological unit, analytical values of rankers or cambisols were given to stony (RK2) or all other (RK1) HRU soil classes, respectively.

Analytical data on organic soils (histosols (O), dystric histosols (O), eutric histosols (O, and gelic histosols (Ox)) are not available in WISE. Soil analytical parameters for organic soils were estimated from the soil horizon data on three histosol soil profiles (Od) available in global soil profile database compiled by ISRIC (Batjes 1995), WOFOST model default soil input files for Europe (Boogaart et al. 1998) and published reference information on soils of the world (FAO-UNESCO 1974, Dreissen at al. 2001) as follows.

Organic soils were assumed as being homogenous over the soil profile and therefore the same analytical values were given to all soil profile depth intervals considered in WISE dataset (five intervals to depth of 1 m). Median of soil albedo interval for dark soil surfaces (0.15) given by Dobos (2006) was set for soil albedo parameter. Arbitrary value (0) was set to volume of stones and calcium carbonate content soil parameters. For the presence of ground water table close to the soil surface in most of organic soils (Driessen et al. 2001) and relatively low value of saturated hydraulic conductivity taken from WOFOST input files soil hydrological group was interpreted as D. Data on representative textural class of organic soils was not available and it was arbitrary set for all organic soils to 30, 40 and 30 for sand, silt and clay fraction, respectively, so that any soil textural extreme is eliminated from simulations. Upper limit of bulk density interval for fibric histosols (0.15 t/m^3) published by Driessen et al. (2001) was given to all organic soils. Cation exchange capacity was calculated as an average across the global soil profile database (Batjes 1995) and set for all organic soils (95 cmol/kg). Base saturation was calculated as an average from global soil profile database (25%) and together with cation exchange capacity value it was used for calculation of base saturation for O, Od and Ox (23.75 cmol/kg). Representative value (75%) of eutric qualifier base saturation interval (50-100%) was taken from DSMW legend (FAO-UNESCO 1974) and used in calculation of base saturation for Oe (71.25 cmol/kg). Average soil pH (4.5) calculated from global soil database (Batjes 1995) was given to O, Od and Ox organic soils. Following both the representative soil pH for eutric histosols given by Driessen at al. (2001) and FAO-UNESCO (1974) eutric histosols class definition soil pH parameter was set to 6.5 for Oe. Soil organic carbon was set to 35 % for all organic soils following the average calculated from global soil profile database (Batjes 1995) and characteristics of histosols given by Driessen et al. (2001). From WOFOST model default soil input files for Europe – EC6 (Boogaart et al. 1998) representative values of 0.52, 0.13, and 5.62 were taken for field water capacity, wilting point and saturated hydraulic conductivity, respectively.

4.3. Cropland management data

Country specific statistics on cultivated crop areas, crop rotation rules, crop management calendar and data on fertilization and other supporting data (various crop classifications and crop specific data) were compiled to satisfy the minimum set of EPIC model requirements for crop management data (APPENDIX 1).

4.3.1. Selection of crops for global database

GLU dataset crop list (chapter 2.4.2) was selected as the primary list of crops to be included in global database. In the final list of crops (Tab. 4.1.) all crop groups included in original GLU dataset (banana and plantains, sweet potato and yams, other pulses, other oil crops, and other fiber crops) were replaced by country specific representative of the crop group. The most frequent crop (as for its harvested area) in the country which was not included in original GLU crop list was taken from FAOSTAT as the crop group representative. If no crop was available for the country in FAOSTAT, the crop group representative of the nearest country was taken.

Final list of crops covers only those crops which are considered globally most important (You et Wood 2006) and many other crops with only regional significance is not included (e.g. temporary pastures or silage corn for most of central and western Europe).

Tab. 4.1: *List of crops assumed in global database.*

CROP ACRONYM IN GLOBAL DATABASE	CROP NAME
BARL	barley
BEAN	beans
CASS	cassava
COFF	coffe
COTT	cotton
GROU	ground nuts
MAIZ	maize
POTA	potatoes
RICE	rice
SORG	sorghum
SOYB	soybean
SUGC	sugarcane
WHEA	wheat
JUTE	jute
BHBE	broad and horse bean
SUNF	sunflower
SWTP	sweet potatoes
BANA	bananas
COCO	coconuts
CPEA	chick peas
FLAX	flax fibre and tow
LENT	lentils
LINS	linseed
MELO	melonseed
MILL	millet
MUST	mustard seed
OLIV	olives
OPAL	oil palm fruits
PEAS	peas, dry
PLAN	plantains

CROP ACRONYM IN GLOBAL DATABASE	CROP NAME
PULS	pulses, nec
RAPE	rapeseed
SAFF	safflower seed
SESA	sesame seed
SISA	sisal
SUGB	sugar beet
YAMS	yams

4.3.2. Crop share and crop rotation rules data

Primary aim of crop share data is to provide a basis for compilation of the hypothetic crop rotations or other crop cultivation strategies (such as plantations) which are to represent the SimU delineation specific land use base-run scenario in bio-physical modeling. Because of lack of relevant data on global scale, multiplied cropping during the year or multi-crop cultivation (more than one crop at the same place and time) was not considered in standing version of global database.

A SimU delineation and management system (high input, irrigated high input, low input and subsistence) specific list of physical areas of all crops from final crop list (further referred as crop share data) was constructed from original GLU data by zonal summing the crop areas over the SimU delineation and consecutively refined to fit the SimU delineation specific land use statistics data (chapter 4.1.2).

Tab. 4.2: *Total duration of cultivation for selected perennial crops.*

CROP	TOTAL LENGTH OF CULTIVATION (years)
sugar cane	4
coffee	25
banana plant	25
plantain plant	25
sisal	15
coconuts palm	70
olive tree	100
oil palm	25

Relevance masks were interpreted and together with various crop classifications included in crop share data table to make possible selection of various crop rotation options which could optionally take a part in base-run scenarios set for SimU delineation:

- Duration of crop cultivation less or more than 365 days was used as a criterion for classification of all crops as annual or perennial. For selected perennial crops the most likely total length of cultivation was interpreted from many available sources as given in table (Tab. 4.2.);
- Based on assumed crop cultivation strategies all crops were distinguished as crops cultivated in rotation or as crops cultivated in monoculture (most of perennial crops and typical plantain crops). For subsistence management system all crops (both annual and perennial) were assumed as they are grown in rotation;

- SimU delineation relevance mask was taken from land cover/land use statistics dataset (chapter 4.1.3) to indicate whether the management system is significant enough to be considered in crop rotation or crop calendar base-run scenario for the particular SimU delineation. Absolute relevance mask was interpreted based on SimU delineation specific management systems areas data coming from land use statistics dataset (chapter 4.1.3) so that only spatially dominant management system can be optionally selected as a representative of the particular SimU delineation in bio-physical simulations;
- Minimum crop area portion of total management system area in particular SimU delineation was set to 5% and used as a criterion for setting up the crop relevance mask. Crop relevance mask is to tell if crop is significant enough to be considered in base-run scenario for SimU delineation;
- In particular management system of some SimU delineations both crops grown in rotation and monoculture crops can be relevant for simulation. Therefore an alternative mask was interpreted to tell which crop cultivation strategy is more significant for particular management system in SimU delineation. Alternative mask was defined based on total area of monoculture crop or sum of all crops grown in rotation in particular SimU delineation and management system.

Tab. 4.3: *Crop rotation rules for global database, main crops in rows, preceding crops in columns (0 – not possible, 1 – not suitable but possible, 2 – suitable and very suitable).*

CROP	BARL	BEAN	CASS	GROU	MAIZ	JUTE	SUNF	BHBE	POTA	RICE	SORG	SOYB	SWTP	WHEA	SUGC	COTT	SUGB	MILL	MUST	SESA	SAFF	RAPE	PEAS	MELO	LINS	LENT	FLAX	CPEA	YAMS	BANA	PLAN
BARL	2	2	2	2	2	1	2	2	2	1	2	2	2	2	1	1	2	1	2	1	1	2	2	1	2	2	2	2	1	1	1
BEAN	2	1	2	1	2	1	2	1	2	1	2	1	2	2	1	2	2	2	1	2	1	1	1	1	2	1	2	1	2	2	2
CASS	1	2	1	2	1	0	0	2	1	0	1	2	1	1	0	0	1	1	1	1	1	1	2	1	0	2	0	2	1	0	0
GROU	2	1	2	1	2	2	2	1	2	2	2	1	2	2	0	1	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2
MAIZ	1	2	2	2	2	0	1	2	2	2	1	2	2	2	1	1	2	1	1	1	1	1	2	1	1	2	1	2	1	1	1
JUTE	1	2	1	2	1	1	1	2	2	2	1	2	0	0	0	0	1	1	1	1	1	1	2	1	1	2	1	2	0	1	1
SUNF	2	1	2	1	2	0	1	1	1	1	2	1	1	2	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
BHBE	2	1	2	1	2	1	2	1	2	1	2	1	2	2	1	1	2	2	1	2	1	2	1	1	1	1	1	1	2	2	2
POTA	2	2	1	2	2	1	0	2	1	1	2	2	1	2	1	1	1	2	2	1	1	2	2	1	2	2	2	2	1	1	1
RICE	2	2	1	2	1	0	1	2	1	2	1	2	1	2	0	0	0	1	1	1	1	1	2	1	1	2	1	2	0	1	1
SORG	2	2	2	2	2	1	1	2	2	1	2	2	2	2	0	2	2	1	1	1	1	1	2	1	2	2	2	2	2	2	2
SOYB	2	1	2	1	2	1	1	1	2	1	2	2	2	2	1	1	2	2	1	1	1	1	1	1	1	1	1	1	2	2	2
SWTP	0	0	1	2	2	1	2	0	1	2	2	1	2	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	2	2
WHEA	2	2	2	2	2	1	2	2	2	2	2	2	2	2	1	2	2	1	2	2	1	2	2	1	2	2	2	2	1	1	1
SUGC	1	2	0	2	2	1	2	2	1	2	2	2	0	1	2	0	1	2	2	2	2	2	2	2	2	2	2	2	0	0	0
COTT	2	2	0	2	2	1	1	2	0	0	2	2	0	2	0	2	0	2	1	1	1	1	2	1	1	2	1	2	0	0	0
SUGB	2	2	0	2	1	1	1	2	1	0	1	2	1	2	0	0	1	1	2	1	1	1	2	1	2	2	2	2	1	1	1
MILL	1	2	1	2	1	1	2	2	2	1	1	2	2	1	1	1	2	1	1	1	1	1	2	1	1	2	1	2	2	2	2
MUST	2	2	1	2	1	1	1	2	2	0	1	2	1	2	1	1	1	1	2	2	1	1	2	1	2	2	2	2	1	1	1
SESA	2	2	1	2	2	1	1	2	2	2	2	2	1	2	1	2	1	2	1	1	1	1	2	1	1	2	1	2	1	1	1
SAFF	2	1	1	2	2	1	1	2	2	1	2	2	1	1	1	1	1	2	1	2	1	1	2	1	1	2	1	2	1	1	1
RAPE	2	2	1	2	2	0	1	1	1	1	0	2	2	2	1	1	0	2	1	1	1	1	2	1	1	2	1	2	2	1	1
PEAS	2	1	2	1	2	1	2	1	2	1	2	1	2	2	1	2	2	2	2	2	1	2	1	1	2	1	2	1	2	1	1
MELO	2	2	1	2	2	1	1	2	1	1	2	2	1	2	1	1	1	1	1	1	1	1	2	1	1	2	1	2	1	2	2
LINS	2	1	1	1	2	1	1	1	1	1	2	1	1	2	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1
LENT	2	1	2	1	2	1	2	1	2	1	2	1	2	2	1	2	2	2	2	2	1	2	1	1	2	1	2	1	2	1	1
FLAX	2	1	1	1	2	1	1	1	1	1	2	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	2	2
CPEA	2	1	2	1	2	1	2	1	2	1	2	1	2	2	1	2	2	2	2	2	1	2	1	1	2	1	2	1	2	1	1
YAMS	0	0	1	2	2	1	2	0	1	1	2	1	0	0	0	0	1	2	1	1	1	1	0	1	1	0	1	0	2	2	2
BANA	1	2	0	2	2	1	1	2	2	2	2	2	2	1	0	0	1	2	1	1	1	1	2	1	1	2	1	2	0	1	1
PLAN	1	2	0	2	2	1	1	2	2	2	2	2	2	1	0	0	1	2	1	1	1	1	2	1	1	2	1	2	0	2	2

A crop rotation rules table compiled for Europe (Schmid et al. 2006) was after slight modifications and completing of missing crops from final list of crop (Tab. 4.1) taken as the basis for global crop rotation rules table. Based on general knowledge on crop-after-crop suitability in rotation and crop calendar data (chapter 4.3.3) a crop combination suitability in rotation was classified into three classes as follows: i) very suitable to suitable (the crops are usually grown in mutual combination), ii) not suitable but possible (crops are not usually grown in mutual combinations or such combination is not recommended but there are not physical restrictions such as overlapping planting/harvesting dates to cultivate crops in combination), and iii) absolutely not suitable (physical restrictions such as overlapping dates of planting/harvesting make crop combination in rotation impossible). Crop rotation rules as it was set for global database are given in the table (Tab. 4.3).

4.3.3. Crop calendar data

A country and crop specific crop calendar from FAOAQUASTAT covering developing countries in tropical and subtropical regions was used as a basic source of data on starting and end decades for crop planting and harvesting. FAOAQUASTAT dataset was completed with other available sources such as USDA document published global scale data on crop management calendar, European regional data (MARS), and national (chapter 2.3.2, APPENDIX 2) or crop specific (chapter 2.3.2) crop management calendar data and table of country and crop specific start and end period of planting and harvesting was created. The resulting table was compared against the country specific crop share data (chapter 4.3.2) and all identified gaps in crop data were filled up by country specific crop calendar of crop with similar cultivation requirements as missing crop (Tab 4.4) or by crop calendar of the same crop from the nearest country.

Tab. 4.4: *Rules for filling up the gaps in missing crops crop calendar data, intepreted from IFA 1992 and Jurášek 1997, 1998 published data.*

ALTERNATIVE CROP	CROPS
maize	sorghum, millet, sunflower
bean	pea abd other pulses
soybean	groundnut
jute	groundnut
sunflower	safflower, maize

Mostly for large countries but also for all other countries with heterogonous natural conditions it is useful if crop calendar data can be interpreted in the way it respects the best the regional particularities. At global scale, however, such data is missing for the most of the countries. Therefore in the global database sub-country national level was used only for small group of large countries respecting the actually available published information. Countries and assumed sub-country regions are listed in table (Tab. 4.5).

The table of starting and end planting/harvesting periods compiled from available sources was then used for calculation of planting and harvesting dates so that they represented middle of reported planting or harvesting period. Length of vegetation period was calculated as difference (in days) of harvesting and planting day and used for final refinements of planting or harvesting dates in case calculated vegetation length value seriously exceeded published data on typical lengths of vegetation periods given in table (Tab. 4.6).

Tab. 4.5: *Countries and assumed sub-country regions for crop calendar data specification (regions according to crop calendar data source used for the country).*

COUNTRY	SUB-COUNTRY REGION
Australia	New South Wales
Australia	Northern Territory
Australia	Queensland
Australia	South Australia
Australia	Victoria
Australia	Western Australia
Brazil	centre-south
Brazil	north
Brazil	north-east
Brazil	south
Canada	Canadian Prairies
Canada	Ontario and Quebec
China	centre
China	north
China	south
Russian Federation	Central
Russian Federation	Siberia
Russian Federation	South
Russian Federation	Ural

Because of lack of relevant global scale data on agricultural management operations it was set arbitrary based on planting and harvesting dates as follows:

- One tillage operation (ploughing) has been set for all crops cultivated in all management systems. The plughing date has been set ten days before planting;
- Manure application has been set for all crops cultivated in high input, irrigated, and low input systems one day before ploughing;
- Nitrogen application has been assumed as it is done on two separate dates for crops cultivated in high input, irrigated and low input management systems. The first application is done before planting and the date is set three days before ploughing. One half of calculated nitrogen rate (chapter 4.3.4) is applied during the first application. The second application is done during the vegetation. The date of second nitrogen application has been for all annual crops set to half of vegetation period, for perennial crops the date has been set to the first year of the cultivation so that the nitrogen is applied in the middle of the period defined by planting date and end of the first year of cultivation. One half of calculated nitrogen rate (chapter 4.3.4) is applied during the second application. Total calculated nitrogen rate (chapter 4.3.4) is applied for selected perennial crops (cassava, sugar cane, banana, and plantains) in the second or third year of cultivation on the middle of the period between start of the second or third (cassava) cultivation year and date of harvest (cassava) or first harvest (sugar cane, banana, and plantain);
- Slightly modified nitrogen application scheme from that above has been set for perennial crops from table (Tab. 4.2) with exception of the sugar cane, banana, and plantains. First year nitrogen application is done the same way as for all other crops. In the second and

each other years of cultivation the nitrogen applied in two separate dates so that the first nitrogen application date is 121 days before the harvest date and the second 121 days after the harvest date. The dates of nitrogen application are refined in that manner that two nitrogen applications are to be done during one cultivation year;

- Phosphorous and potassium application has been set on only one date before planting or during vegetation period (in second and each other years for perennial crops from Tab 4.2. and cassava) together with nitrogen application;
- Due to lack of consistent data on irrigation water amounts on global scale the irrigation dates for crops cultivated in irrigated management system were not set in the standing version of global database.

Tab. 4.6: *Typical lengths of vegetation period (in days) for most of global database relevant crops (minimum, maximum and average lengths) as published by IFA 1992 and Jurášek 1997, 1998.*

CROP	IFA, 1992		Jurášek 1997, 1998	
	MIN-MAX	AVERAGE	MIN-MAX	AVERAGE
Rice	70 - 160	115	90 - 210	150
Maize	60 - 280	170	90 - 150	120
Wheat	180 - 270	225	120 - 210	165
Barley	0	0	90 - 120	105
Sorghum	105 - 270	188	90 - 210	150
Millet	75 - 300	188	60 - 90	75
Potato	0	0	90 - 210	150
Sweet potato	120 - 180	150	120 - 180	150
Cassava	300 - 365	332,5	365 - 730	548
Yams	210 - 405	308	0	0
Bean	180 - 285	233	0	0
Pea	165 - 255	210	0	0
Chickpea	75 - 180	128	0	0
Lentil	90 - 165	128	0	0
Soybean	90 - 150	120	80 - 160	120
Groundnut	120 - 145	133	90 - 150	120
Sunflower	120 - 160	140	90 - 150	120
Oilseed Rape	320	320	270	270
Safflower	120	120	0	0
Olive_firt harvest	3 y.	3 y.	4 - 12 y.	8
Coconut_first harvest	4,5 y.	4 1/2 y.	6 - 9 y.	7 1/2
Oilpalm	2 1/2 - 3 1/2	3	3 - 4 y.	3 1/2
Sugarcane	300 - 720	510	300 - 690	495
Sugar beet	0	0	180 - 240	210
Cotton	140 - 210	175	160 - 220	190
Flax	90 - 120	105	0	0
Jute	90 - 150	120	90 - 150	120
Sisal_first harvest	900	900	0	0
Coffee_first harvest	720 - 1080	900	4*	4*
Banana	210 - 450	220	270 - 365	318

4.4.4. Fertlization rates

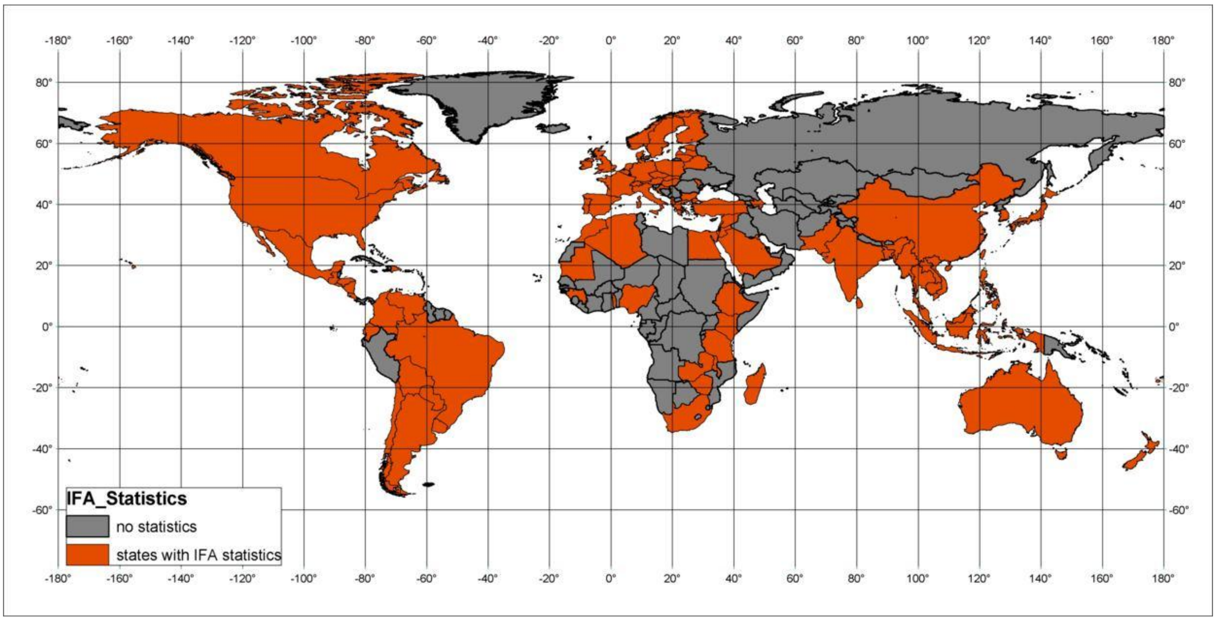
Fertilization rates data were treated separately for manure application (and nitrogen rate coming from manure application) and N,P, and K fertilizers application.

High resolution data on nitrogen rates coming from manure application were averaged over the SimU delineation by zonal statistics algorithm and yielded value was treated so that it did not exceed arbitrary set maximum value of 300 kg/ha of nitrogen. Consecutively, a coefficient 0.002 reported by (Williams et al. 1995) as default value of nitrogen amount coming from manure was used for calculation of total manure application from manure data.

For countries covered by IFA statistics the country and crop specific information on fertilization rates (kg/ha) of nitrogen (N), phosphorous (P_2O_5), and potassium (K_2O) were taken directly for high input and irrigated management systems, for low input system the application rate was decreased to one half of total application rate reported in IFA. No fertilization is aasumed for subsistence management system.

For other countries not covered by IFA statistics (Fig. 4.1) as well as for all the crops of IFA countries which are not covered by the statistics FAOSTAT country-level data on total fertilizer consumption (1000t) was recalculated to crop not-specific application rates (kg/ha) by simple algorithm taking into account particular management system.

Fig. 4.1: *Countries covered and not covered by IFA fertilizer application rates statistics.*



Country specific high input and irrigated management systems areas were summed and their area portion calculated from total cropland area. The same was done for low input management system. Yielded area portions were used for allocation of total fertilizer application amounts to management systems. Low input management system area portion decreased to one half was used as coefficient for allocation total fertilizers amount (1000t) applied in low input system in particular country, the rest of total fertilizer application amounts was allocated to high input and irrigated management systems. Final value of fertilizers application rate for a particular country (kg/ha) was then calculated as total allocated amount divided by the corresponding management systems areas. The origin of fertilization rate data has been flagged in the metadata fields of fertilization rate table.

Consecutively, calculated rates were refined so that it fit arbitrary set maximum values of 350 kg/ha or 175 kg/ha of N for high input and irrigated or low input management systems, respectively. Similarly a maximum rates of P_2O_5 and K_2O application rates were set to 300 kg/ha or 150 kg/ha for high input and irrigated or low input management systems, respectively.

Additional rules were applied for all pulses including soybean and groundnuts and flagged in the table so that nitrogen is applied only before harvest and maximum nitrogen application rate has been set to 90 kg/ha or 45 kg/ha for high input and irrigated management system or low input management system, respectively. For all management systems in the country having no corresponding area relevant for simulation, fertilizer application rate was arbitrary set to not-relevant (-999).

4.5. Weather data

Those EPIC model required weather parameters available from Tyndall dataset were directly taken and included in global database. Some other weather parameters were interpreted based on available data. Number of wet days was calculated by simple quadratic equation *Wet_days = α*sqrt(total_precipitation)*, where α was estimated for each grid cell with the precipitation and the number of wet days in the past (Schmid et al. 2006). The radiation was estimated from cloudiness data by the method described by Rivington et al. (2002) where the radiation is treated as a function of day length, latitude, atmospheric transmissivity, solar declination and solar elevation. Original as well as calculated parameters for the past were calculated as averages of different time intervals (10, 25, 50 and 100 years) for each climatic variable.

The variation data and probability values (standard deviation of minimal, maximal temperature and precipitation, skewness of precipitation, number of rainy days, probabilities of wet day after wet day and wet day after dry day) were calculated from daily sequences of ECWMF weather data. The probabilities of wet after wet and wet after dry day were calculated as follows: a number of wet-wet or dry-wet sequences together with dry and wet days was calculated for each month. Consecutively, the ratio of wet-wet vs. wet and dry-wet vs. dry was calculated. If the number of wet (or dry) days was effectively zero, a missing value was returned. Alternatively a non-informative Bayesian correction may be used so that for example PW|W = (wet-wet + 1)/(wet + 2).

5. Global database data structure

GEO-BENE global database for bio-physical modeling v. 1.0 is organized in four individual thematic datasets and one spatial reference dataset for geographical representation and visualization of thematic data:

- Spatial reference dataset (chapter 5.1);
- Land cover and Land use dataset (chapter 5.2);
- Topography and Soil dataset (chapter 5.3);
- Cropland management dataset (chapter 5.4);
- Climate dataset (chapter 5.5)

5.1. Spatial reference database (SpatialReference_v10)

Purpose of spatial reference dataset and domain tables is to reference and visualize thematic data of global database. Database is implemented in MS Office Access 2003 database. All tables and attribute fields contains metadata descriptions. One data table, four domain tables and one select query are included in the *SpatialReference_v10* database:

- *SpatialReference* data table, 5' spatial resolution grid centroid lattice, spatial reference for display global database content, includes all attributes necessary for SimU and HRU*PX30 zone delineation and relevant land cover/land use class visualization masks; (Tab. 5.1);
- *D_HRUalti* domain table, list and description of altitude classes used for HRU delineation (Tab. 5.2);
- *D_HRUslp* domain table, list and description of slope classes used for HRU delineation (Tab. 5.3);
- *D_HRUsoilgrp* domain table, list and description of soil classes used for HRU delineation (Tab. 5.4);
- *D_COUNTRY* domain table, list of countries used for global database, country identification numbers, country names and acronyms according to United Nations Statistics Division (Tab. 5.5);
- *D_ColRow30* domain table, split col_row30 identification into two separate fields (col30, row30), only for export data to EPIC (Tab. 5.6);
- *SpatialReference(DataPreview&EXPORT)* select query set on *SpatialReference* data table, helps with the spatial reference data preview and export the data, use of select query is optional (SQL code of query is given in APPENDIX 3);

Tab. 5.1: *SpatialReference data table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
Col_Row	*Text(50)*	identification of 5' spatial resolution pixel (column and row number), counted from upper left corner;
XCOORD	*Number(Double)*	5' spatial resolution pixel centroid x coordinate (decdeg), can be used for data visualisation;
YCOORD	*Number(Double)*	5' spatial resolution pixel centroid y coordinate (decdeg), can be used for data visualisation;

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
PxArea	*Number(Double)*	real area (ha) of 5' spatial resolution pixel;
HRU	*Number(Integer)*	homogenous response unit (HRU) code, assembled of the code of AltiClass (first character), SlpClass (second character) and SoilClass (third character), 88 - soil class = 88 (no-soil prevails);
Col_Row30	*Text(50)*	identification of 30' spatial resolution pixel (column and row number), counted from upper left corner;
COUNTRY	*Number(Integer)*	country code, numerical code by United Nations Statistics Division;
ZoneID	*Number(LongInteger)*	HRU*PX30 zone number, can be used for display HRU*PX30 zone related data geographicaly via spatial reference (topography and soil data);
SimUID	*Number(LongInteger)*	SimU delineation (HRU*PX30*COUNTRY) zone number, can be used for display SimU delineation related data via spatial reference (land cover/land use data, crop management data);
mCrpLnd	*Number(Byte)*	cropland relevant data visualisation mask, (1 = data is visualized, 0 = data is not visualized), based on arbitrary set rules;
mCrpLnd_H	*Number(Byte)*	cropland (high input management system) relevant data visualisation mask, (1 = data is visualized, 0 = data is not visualized), based on arbitrary set rules;
mCrpLnd_L	*Number(Byte)*	cropland (low input management system) relevant data visualisation mask, (1 = data is visualized, 0 = data is not visualized), based on arbitrary set rules;
mCrpLnd_I	*Number(Byte)*	cropland (irrigated high input management system) relevant data visualisation mask, (1 = data is visualized, 0 = data is not visualized), based on arbitrary set rules;
mCrpLnd_S	*Number(Byte)*	cropland (subsistence management system) relevant data visualisation mask, (1 = data is visualized, 0 = data is not visualized), based on arbitrary set rules;
mOthAgri	*Number(Byte)*	other agricultural land relevant data visualisation mask, (1 = data is visualized, 0 = data is not visualized), based on arbitrary set rules;
mGrass	*Number(Byte)*	grassland relevant data visualisation mask, (1 = data is visualized, 0 = data is not visualized), based on arbitrary set rules;
mForest	*Number(Byte)*	forest land relevant data visualisation mask, (1 = data is visualized, 0 = data is not visualized), based on arbitrary set rules;
mWetLnd	*Number(Byte)*	wettland relevant data visualisation mask, (1 = data is visualized, 0 = data is not visualized), based on arbitrary set rules;
mOthNatLnd	*Number(Byte)*	other natural land relevant data visualisation mask, (1 = data is visualized, 0 = data is not visualized), based on arbitrary set rules;
mNotRel	*Number(Byte)*	not-relevant land cover class relevant data visualisation mask, (1 = data is visualized, 0 = data is not visualized), based on arbitrary set rules;

Tab. 5.2: *D_HRUalti domain table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
AltiClass	*Number(Byte)*	altitude class for HRU delineation;
Altitude	*Text(50)*	altitude (m) interval;

Tab. 5.3: *D_HRUslp domain table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
SlpClass	*Number(Byte)*	slope class for HRU delineation;
Slope	*Text(50)*	slope (deg) interval;
RepSlp	*Number(Byte)*	slope class representative value (deg);
RepSlpPerc	*Number(Byte)*	slope class representative value (%) calculated by equation RepSlpPerc = tan(RepSlp*(3,14159/180)*100;

Tab. 5.4: *D_HRUsoilgrp domain table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
SoilClass	*Number(Byte)*	slope class for HRU delineation;
Soil	*Text(50)*	soil texture, stoniness and classification by FAO/UNESCO 1974 (Soil map of the world - legend);

Tab. 5.5: *D_COUNTRY domain table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
COUNTRY	*Number(Integer)*	country code, numerical code by United Nations Statistics Division;
UN_Name	*Text(250)*	country name by United Nations Statistics Division;
UN_Acro	*Text(4)*	acronym of country by United Nations Statistics Division;

Tab. 5.6: *D_ColRow30 domain table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
Col_Row30	*Text(50)*	identification of 30' spatial resolution pixel (column, row), counted from upper left corner;
Col30	*Number(Integer)*	30' spatial resolution grid column number;
Row30	*Number(Integer)*	30' spatial resolution grid row number;

5.2. Land cover and Land use database (LandCover&LandUse_v10)

Purpose of the dataset is to equip the bio-physical and optimization modeling with spatial and statistical data on relevant land covers and particular land uses of arable land. Database is implemented in MS Office Access 2003 database. All tables and attribute fields contains metadata descriptions. Two data table, five domain tables and one select query are included in the *LandCover&LandUse_v10* database:

- *PixelStatistics* data table, global grid pixel specific statistics on land cover/land use (Tab. 5.7);
- *SimUstatistics* data table, SimU delineation (HRU*PX30*COUNTRY zone) aggregated statistics on land cover/land use, SimU delineations having HRU = 88 are excluded (Tab. 5.8);

- *D_HRUalti* domain table, list and description of altitude classes used for HRU delineation (Tab. 5.2, chapter 5.1);
- *D_HRUslp* domain table, list and description of slope classes used for HRU delineation (Tab. 5.3, chapter 5.1);
- *D_HRUsoilgrp* domain table, list and description of soil classes used for HRU delineation (Tab. 5.4, chapter 5.1);
- *D_COUNTRY* domain table, list of countries used for global database, country identification numbers, country names and acronyms according to United Nations Statistics Division (Tab. 5.5, chapter 5.1);
- *D_ColRow30* domain table, split col_row30 identification into two separate fields (col30, row30), only for export data to EPIC (Tab. 5.6, chapter 5.1);
- *SimUstatistics(DataPreview&EXPORT)* select query set on *SimUstatistics* and *D_ColRow30* tables, helps with the SimU statistics preview and export the data, use of select query is optional (SQL code of query is given in APPENDIX 3);

Tab. 5.7: *PixelStatistics data table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
Col_Row	*Text(50)*	identification of 5' spatial resolution pixel (column and row number), counted from upper left corner;
HRU	*Number(Integer)*	homogenous response unit (HRU) code, assembled of the code of AltiClass (first character), SlpClass (second character) and SoilClass (third character), 88 - soil class = 88 (no-soil prevails);
Col_Row30	*Text(50)*	identification of 30' spatial resolution pixel (column and row number), counted from upper left corner;
COUNTRY	*Number(Integer)*	country code, numerical code by United Nations Statistics Division;
SimUID	*Number(LongInteger)*	SimU delineation (HRU*PX30*COUNTRY) zone number, can be used for display SimU delineation related data via spatial reference (land cover/land use data, crop management data);
PxArea	*Number(Double)*	real area (ha) of 5' spatial resolution pixel;
CrpLnd	*Number(Double)*	cropland, total, physical area (ha);
CrpLnd_H	*Number(Double)*	cropland, high input management system, physical area (ha);
CrpLnd_L	*Number(Double)*	cropland, low input management system, physical area (ha);
CrpLnd_I	*Number(Double)*	cropland, irrigated high input management system, physical area (ha);
CrpLnd_S	*Number(Double)*	cropland, subsistence management system, physical area (ha);
OthAgri	*Number(Double)*	other agricultural land (other than cropland), physical area (ha);
Grass	*Number(Double)*	grassland, physical area (ha);
Forest	*Number(Double)*	forest, physical area (ha);
WetLnd	*Number(Double)*	wetland, physical area (ha);
OthNatLnd	*Number(Double)*	other natural land, physical area (ha);
NotRel	*Number(Double)*	not relevant land, physical area (ha);
Flag	*Number(Byte)*	metadata field, identification of method used for land cover data narmonization in particular case: 1 (CrpLnd > PxArea), 2 (CrpLnd > total agricultural area), 3 (CrpLnd < total agricultural area), 4 (CrpLn = 0);

Tab. 5.8: *SimUstatistics data table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
SimUID	*Number(LongInteger)*	SimU delineation (HRU*PX30*COUNTRY) zone number, can be used for display SimU delineation related data via spatial reference (land cover/land use data, crop management data);
HRU	*Number(Integer)*	homogenous response unit (HRU) code, assembled of the code of AltiClass (first character), SlpClass (second character) and SoilClass (third character), 88 - soil class = 88 (no-soil prevails);
Col_Row30	*Text(50)*	identification of 30' spatial resolution pixel (column and row number), counted from upper left corner;
COUNTRY	*Number(Integer)*	country code, numerical code by United Nations Statistics Division;
SimUArea	*Number(Double)*	real area (ha) of SimU delineation;
CrpLnd	*Number(Double)*	cropland, total, physical area (ha);
CrpLnd_H	*Number(Double)*	cropland, high input management system, physical area (ha);
CrpLnd_L	*Number(Double)*	cropland, low input management system, physical area (ha);
CrpLnd_I	*Number(Double)*	cropland, irrigated high input management system, physical area (ha);
CrpLnd_S	*Number(Double)*	cropland, subsistence management system, physical area (ha);
OthAgri	*Number(Double)*	other agricultural land (other than cropland), physical area (ha);
Grass	*Number(Double)*	grassland, physical area (ha);
Forest	*Number(Double)*	forest, physical area (ha);
WetLnd	*Number(Double)*	wetland, physical area (ha);
OthNatLnd	*Number(Double)*	other natural land, physical area (ha);
NotRel	*Number(Double)*	not relevant land, physical area (ha);
mCrpLnd	*Number(Byte)*	cropland relevance for SimU delineation zone (1 = relevant, 0 = not relevant), relevant if CrpLnd/SimUArea > 0.05;
mCrpLnd_H	*Number(Byte)*	cropland (high input management system) relevance for SimU delineation zone (1 = relevant, 0 = not relevant), relevant if CrpLnd_H/SimUArea > 0.05;
mCrpLnd_L	*Number(Byte)*	cropland (lowinput management system) relevance for SimU delineation zone (1 = relevant, 0 = not relevant), relevant if CrpLnd_L/SimUArea > 0.05;
mCrpLnd_I	*Number(Byte)*	cropland (irrigated high input management system) relevance for SimU delineation zone (1 = relevant, 0 = not relevant), relevant if CrpLnd_I/SimUArea > 0.05;
mCrpLnd_S	*Number(Byte)*	cropland (subsistence management system) relevance for SimU delineation zone (1 = relevant, 0 = not relevant), relevant if CrpLnd_S/SimUArea > 0.05;
mOthAgri	*Number(Byte)*	other agricultural land relevance for SimU delineation zone (1 = relevant, 0 = not relevant), relevant if OthAgri/SimUArea > 0.05;
mGrass	*Number(Byte)*	grassland relevance for SimU delineation zone (1 = relevant, 0 = not relevant), relevant if Grass/SimUArea > 0.05;
mForest	*Number(Byte)*	forest land relevance for SimU delineation zone (1 = relevant, 0 = not relevant), relevant if Forest/SimUArea > 0.05;
mWetLnd	*Number(Byte)*	wetland relevance for SimU delineation zone (1 = relevant, 0 = not relevant), relevant if WetLnd/SimUArea > 0.05;
mOthNatLnd	*Number(Byte)*	other natural land relevance for SimU delineation zone (1 = relevant, 0 = not relevant), relevant if OthNatLnd/SimUArea > 0.05;
mNotRel	*Number(Byte)*	not-relevant land cover classes relevance for SimU delineation zone (1 = relevant, 0 = not relevant), relevant if NotRel/SimUArea > 0.05;

5.3. Topography and soil database (Topography&Soil_v10)

Purpose of the dataset is to provide EPIC model with mandatory data on topography (geographical position, altitude and slope) and soil (soil profile and soil layer related data on soil properties). Database is implemented in MS Office Access 2003 database. All tables and attribute fields contains metadata descriptions. Four data table, five domain tables and two select queries are included in the *Topography&Soil_v10* database:

- *ZoneData* data table, HRU*PX30 zone specific data on geographic position, altitude, slope and the digital map of the world dominat soil typological unit (Tab. 5.9);
- *SoilAnal_MineralSoil* data table, the digital soil map of the world soil typological unit specific soil analytical data for 5 soil depth intervals (0.0 - 0.2m, 0.2 - 0.4m, 0.4 - 0.6m, 0.8 - 1.0m), mineral soils (Tab. 5.10);
- *SoilAnal_OrganicSoil* data table, the digital soil map of the world soil typological unit specific soil analytical data for 5 soil depth intervals (0.0 - 0.2m, 0.2 - 0.4m, 0.4 - 0.6m, 0.8 - 1.0m), organic soils (Tab. 5.11);
- *ClimateReference* data table, assignes historical climate data pixel (5' spatial resolution) to *HRU*PX30* zone by *Col_Row30* identification (Tab. 5.12);
- *D_HRUalti* domain table, list and description of altitude classes used for HRU delineation (Tab. 5.2, chapter 5.1);
- *D_HRUslp* domain table, list and description of slope classes used for HRU delineation (Tab. 5.3, chapter 5.1);
- *D_HRUsoilgrp* domain table, list and description of soil classes used for HRU delineation (Tab. 5.4, chapter 5.1);
- *D_COUNTRY* domain table, list of countries used for global database, country identification numbers, country names and acronyms according to United Nations Statistics Division (Tab. 5.5, chapter 5.1);
- *D_ColRow30* domain table, split col_row30 identification into two separate fields (col30, row30), only for export data to EPIC (Tab. 5.6, chapter 5.1);
- *Topo&Soil_MineralSoil(DataPreview&EXPORT)* select query set on *ZoneData*, *SoilAnal_MineralSoil*, *ClimateReference* and *D_ColRow30* tables, helps with the topo&soil data preview and export, use of select query is optional (SQL code of query is given in APPENDIX 3);
- *Topo&Soil_OrganicSoil(DataPreview&EXPORT)* select query set on *ZoneData*, *SoilAnal_OrganicSoil*, *ClimateReference* and *D_ColRow30* tables, helps with the topo&soil data preview and export, use of select query is optional (SQL code of query is given in APPENDIX 3);

Tab. 5.9: *ZoneData data table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
ZoneID	*Number(LongInteger)*	HRU*PX30 zone number, can be used for display HRU*PX30 zone related data geographicaly via spatial reference (topography and soil data);
HRU	*Number(Integer)*	homogenous response unit (HRU) code, assembled of the code of AltiClass (first character), SlpClass (second character) and SoilClass (third character), 88 - soil class = 88 (no-soil prevails);
Col_Row30	*Text(50)*	identification of 30' spatial resolution pixel (column and row number), counted from upper left corner;

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
ZoneLon	*Number(Double)*	HRU*PX30 zone specific longitude (decimal degrees), x coordinate of 30' spatial resolution grid pixel centroid;
ZoneLat	*Number(Double)*	HRU*PX30 zone specific latitude (decimal degrees), y coordinate of 30' spatial resolution grid pixel centroid;
ZoneArea	*Number(Double)*	HRU*PX30 zone real area (ha);
ZoneAlti	*Number(LongInteger)*	HRU*PX30 zone mean altitude(m);
ZoneSlp	*Number(Byte)*	HRU*PX30 zone representative slope (%), derived as the mean value of the HRU slope class interval;
ZoneSTU	*Text(3)*	HRU*PX30 zone dominant digital map of the world soil typological unit, soil unit code according to FAO map of soils of the world legened (FAO 1974), no-soils (RK1, RK2, ST, NA, DS) according to WISE (Batjes 2006);

Tab. 5.10: *SoilAnal_MineralSoil data table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
ZoneSTU	*Text(3)*	HRU*PX30 zone dominant digital map of the world soil typological unit, soil unit code according to FAO map of soils of the world legened (FAO 1974), no-soils (RK1, RK2, ST, NA, DS) according to WISE (Batjes 2006);
HG	*Number(Byte)*	soil hydrological group by USDA NRCS technical manual, 1 = A, 2 = B, 3 = C, 4 = D;
ALB	*Number(Single)*	albedo of moist soil surface; arbitrary set constant (albedo = 0,15);
DEPTH1	*Number(Single)*	depth of lower boundary of 1. soil layer (m), 0.2;
DEPTH2	*Number(Single)*	depth of lower boundary of 2. soil layer (m), 0.4;
DEPTH3	*Number(Single)*	depth of lower boundary of 3. soil layer (m), 0.6;
DEPTH4	*Number(Single)*	depth of lower boundary of 4. soil layer (m), 0.8;
DEPTH5	*Number(Single)*	depth of lower boundary of 5. soil layer (m), 1.0;
VS1	*Number(Integer)*	volume of stones (%), content of soil fragments > 2mm; WISE (Batjes 2006) value;
VS2	*Number(Integer)*	as above;
VS3	*Number(Integer)*	as above;
VS4	*Number(Integer)*	as above;
VS5	*Number(Integer)*	as above;
SAND1	*Number(Integer)*	sand content (%), WISE (Batjes 2006) value;
SAND2	*Number(Integer)*	as above;
SAND3	*Number(Integer)*	as above;
SAND4	*Number(Integer)*	as above;
SAND5	*Number(Integer)*	as above;
SILT1	*Number(Integer)*	silt content (%), WISE (Batjes 2006) value;
SILT2	*Number(Integer)*	as above;
SILT3	*Number(Integer)*	as above;
SILT4	*Number(Integer)*	as above;
SILT5	*Number(Integer)*	as above;
CLAY1	*Number(Integer)*	clay content (%), WISE (Batjes 2006) value;
CLAY2	*Number(Integer)*	as above;
CLAY3	*Number(Integer)*	as above;
CLAY4	*Number(Integer)*	as above;

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
CLAY5	*Number(Integer)*	as above;
BD1	*Number(Single)*	bulk density (t/m3), WISE (Batjes 2006) value;
BD2	*Number(Single)*	as above;
BD3	*Number(Single)*	as above;
BD4	*Number(Single)*	as above;
BD5	*Number(Single)*	as above;
CEC1	*Number(Single)*	cation exchange capacity (cmol/kg), WISE (Batjes 2006) value;
CEC2	*Number(Single)*	as above;
CEC3	*Number(Single)*	as above;
CEC4	*Number(Single)*	as above;
CEC5	*Number(Single)*	as above;
SB1	*Number(Single)*	sum of bases (cmol/kg), WISE (Batjes 2006) derived value by equation SB = WISE base saturation/100)* WISE CEC;
SB2	*Number(Single)*	as above;
SB3	*Number(Single)*	as above;
SB4	*Number(Single)*	as above;
SB5	*Number(Single)*	as above;
PH1	*Number(Single)*	pH in H2O, WISE (Batjes 2006) value;
PH2	*Number(Single)*	as above;
PH3	*Number(Single)*	as above;
PH4	*Number(Single)*	as above;
PH5	*Number(Single)*	as above;
CARB1	*Number(Single)*	(calcium) carbonate content (%), WISE (Batjes 2006) derived value by equation CARB = WISE total carbonate equivalent/1000g)*100;
CARB2	*Number(Single)*	as above;
CARB3	*Number(Single)*	as above;
CARB4	*Number(Single)*	as above;
CARB5	*Number(Single)*	as above;
CORG1	*Number(Single)*	soil organic carbon content, WISE (Batjes 2006) derived value by equation CORG = WISE organic carbon content/1000g)*100;
CORG2	*Number(Single)*	as above;
CORG3	*Number(Single)*	as above;
CORG4	*Number(Single)*	as above;
CORG5	*Number(Single)*	as above;
FWC1	*Number(Double)*	water content in soil (mm/mm) at field water capacity, WISE (Batjes 2006) sand,silt,clay and BD derived value (Rosetta model and Van Genuchten equation);
FWC2	*Number(Double)*	as above;
FWC3	*Number(Double)*	as above;
FWC4	*Number(Double)*	as above;
FWC5	*Number(Double)*	as above;
WP1	*Number(Double)*	water content in soil (mm/mm) at wilting point, WISE (Batjes 2006) sand,silt,clay and BD derived value (Rosetta model and Van Genuchten equation);
WP2	*Number(Double)*	as above;
WP3	*Number(Double)*	as above;
WP4	*Number(Double)*	as above;

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
WP5	*Number(Double)*	as above;
KS1	*Number(Double)*	saturated hydraulic conductivity (mm/hour) of saturated soil, WISE (Batjes 2006) sand,silt,clay and BD derived value (Rosetta model);
KS2	*Number(Double)*	as above;
KS3	*Number(Double)*	as above;
KS4	*Number(Double)*	as above;
KS5	*Number(Double)*	as above;

Tab. 5.11: *SoilAnal_OrganicSoil data table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
ZoneSTU	*Text(3)*	HRU*PX30 zone dominant digital map of the world soil typological unit, soil unit code according to FAO map of soils of the world legened (FAO 1974), no-soils (RK1, RK2, ST, NA, DS) according to WISE (Batjes 2006);
HG	*Number(Byte)*	soil hydrological group by USDA NRCS technical manual, 1 = A, 2 = B, 3 = C, 4 = D;
ALB	*Number(Single)*	albedo of moist soil surface; arbitrary set constant (albedo = 0,15);
DEPTH1	*Number(Single)*	depth of lower boundary of 1. soil layer (m), 0.2;
DEPTH2	*Number(Single)*	depth of lower boundary of 2. soil layer (m), 0.4;
DEPTH3	*Number(Single)*	depth of lower boundary of 3. soil layer (m), 0.6;
DEPTH4	*Number(Single)*	depth of lower boundary of 4. soil layer (m), 0.8;
DEPTH5	*Number(Single)*	depth of lower boundary of 5. soil layer (m), 1.0;
VS1	*Number(Integer)*	volume of stones (%), arbitrary set to zero;
VS2	*Number(Integer)*	as above;
VS3	*Number(Integer)*	as above;
VS4	*Number(Integer)*	as above;
VS5	*Number(Integer)*	as above;
SAND1	*Number(Integer)*	sand content (%), arbitrary set to 30, soil texture assumed to be ballanced as for sand, silt and clay fractions portion;
SAND2	*Number(Integer)*	as above;
SAND3	*Number(Integer)*	as above;
SAND4	*Number(Integer)*	as above;
SAND5	*Number(Integer)*	as above;
SILT1	*Number(Integer)*	silt content (%), arbitrary set to 40, soil texture assumed to be ballanced as for sand, silt and clay fractions portion;
SILT2	*Number(Integer)*	as above;
SILT3	*Number(Integer)*	as above;
SILT4	*Number(Integer)*	as above;
SILT5	*Number(Integer)*	as above;
CLAY1	*Number(Integer)*	clay content (%), arbitrary set to 30, soil texture assumed to be ballanced as for sand, silt and clay fractions portion;
CLAY2	*Number(Integer)*	as above;
CLAY3	*Number(Integer)*	as above;
CLAY4	*Number(Integer)*	as above;
CLAY5	*Number(Integer)*	as above;
BD1	*Number(Single)*	bulk density (t/m3), set to upper limit of bulk density interval for fibric histosols given by Dreissen et al. 2001;

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
BD2	*Number(Single)*	as above;
BD3	*Number(Single)*	as above;
BD4	*Number(Single)*	as above;
BD5	*Number(Single)*	as above;
CEC1	*Number(Single)*	cation exchange capacity (cmol/kg); set to 95, average value calculated from WISE database (Batjes 1995) data on soil layers of three Od profiles from Guayana, Phillipines and New Zealand;
CEC2	*Number(Single)*	as above;
CEC3	*Number(Single)*	as above;
CEC4	*Number(Single)*	as above;
CEC5	*Number(Single)*	as above;
SB1	*Number(Single)*	sum of bases (cmol/kg); calculated as CEC *0,25 (O, Od, Ox) or CEC*0,75 (Oe), 0,25 is average base saturation calculated from WISE profiles (Batjes 1995), 0.75 is median of 0,5-1 base saturation interval defined for eutric qualifier (FAO-UNESCO 1974);
SB2	*Number(Single)*	as above;
SB3	*Number(Single)*	as above;
SB4	*Number(Single)*	as above;
SB5	*Number(Single)*	as above;
PH1	*Number(Single)*	pH in H2O; set to 4,5 for O, Od, Ox (avg calculated from WISE profiles, Batjes 1995) or to 6,5 for Oe (arbitrary value based on FAO-UNESCO 1974 and Dreissen et al. 2001 characteristics of eutric histosols);
PH2	*Number(Single)*	as above;
PH3	*Number(Single)*	as above;
PH4	*Number(Single)*	as above;
PH5	*Number(Single)*	as above;
CARB1	*Number(Single)*	(calcium) carbonate content (%), arbitrary set to zero;
CARB2	*Number(Single)*	as above;
CARB3	*Number(Single)*	as above;
CARB4	*Number(Single)*	as above;
CARB5	*Number(Single)*	as above;
CORG1	*Number(Single)*	organic carbon content, set to 35 based on WISE profile (Batjes 1995) average and FAO-UNESCO 1974 class definition of histosols;
CORG2	*Number(Single)*	as above;
CORG3	*Number(Single)*	as above;
CORG4	*Number(Single)*	as above;
CORG5	*Number(Single)*	as above;
FWC1	*Number(Double)*	water content in soil (mm/mm) at field water capacity, set to 0.52, adopted from soil input file for european peat soil (EC6) available in WOFOST model (version 7.1, Boogaard et al. 1998);
FWC2	*Number(Double)*	as above;
FWC3	*Number(Double)*	as above;
FWC4	*Number(Double)*	as above;
FWC5	*Number(Double)*	as above;
WP1	*Number(Double)*	water content in soil (mm/mm) at wilting point, set to 0.13, adopted from soil input file for european peat soil (EC6) available in WOFOST model (version 7.1, Boogaard et al. 1998);

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
WP2	*Number(Double)*	as above;
WP3	*Number(Double)*	as above;
WP4	*Number(Double)*	as above;
WP5	*Number(Double)*	as above;
KS1	*Number(Double)*	saturated hydraulic conductivity (mm/hour), set to 5.62, adopted from soil input file for european peat soil (EC6) available in WOFOST model (version 7.1, Boogaard et al. 1998);
KS2	*Number(Double)*	as above;
KS3	*Number(Double)*	as above;
KS4	*Number(Double)*	as above;
KS5	*Number(Double)*	as above;

Tab. 5.12: *ClimateReference data table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
Col_Row30	*Text(50)*	identification of 30' spatial resolution pixel (column and row number), counted from upper left corner;
Tyndall_X	*Number(Double)*	HRU*PX30 zone relevant historical climate data (Tyndall dataset) x-coordinate or longitude (decimal degrees) of the pixel;
Tyndall_Y	*Number(Double)*	HRU*PX30 zone relevant historical climate data (Tyndall dataset) y-coordinate or latitude (decimal degrees) of the pixel;
Flag	*Number(Byte)*	metadata field, flag1 = 1 if no counterpart pixel to 30' spatial resolution pixel was found in climate dataset and Tyndall_X(Y) of the nearest pixel was used instead;

5.4. Cropland management database (CroplandManagement_v10)

Purpose of the dataset is to provide EPIC model with data on crop management alternatives and crop shares within the particular land use, crop and crop management calendar (dates of planting, harvesting, tillage, fertilization and irrigation) and inputs to agriculture (fertilizer application rates). Database is implemented in MS Office Access 2003 database. All tables and attribute fields contains metadata descriptions. Seven data table, five domain tables and three select queries are included in the *CroplandManagement_v10* database:

- *CropCalendar* data table, country and crop specific crop management operation calendar; (Tab. 5.13);
- *CropShare* data table, SimU and management system specific list of crops (crop share), includes data on physical crops area and relevance masks for selection the alternatives (Tab. 5.14);
- *FertilizerApplication* data table, country and crop specific N, P, K fertilizer application rates (Tab. 5.15);
- *ManureApplication* data table, SimU delineation specific data on N comming from manure (application rates) and total manure application (Tab. 5.16);
- *CropIdentification* data table, list of original IFPRI dataset crops and crop groups and all crop country alternatives for IFPRI data crop groups (Tab. 5.17);

- *CropRotationRules* data table, main crop suitability for cultivation after the preceeding crop, rules; (Tab. 5.18);
- *CropDuration* data table, duration of crop cultivation for perennial crops (Tab. 5.19);
- *D_HRUalti* domain table, list and description of altitude classes used for HRU delineation (Tab. 5.2, chapter 5.1);
- *D_HRUslp* domain table, list and description of slope classes used for HRU delineation (Tab. 5.3, chapter 5.1);
- *D_HRUsoilgrp* domain table, list and description of soil classes used for HRU delineation (Tab. 5.4, chapter 5.1);
- *D_COUNTRY* domain table, list of countries used for global database, country identification numbers, country names and acronyms according to United Nations Statistics Division (Tab. 5.5, chapter 5.1);
- *D_ColRow30* domain table, split col_row30 identification into two separate fields (col30, row30), only for export data to EPIC (Tab. 5.6, chapter 5.1);
- *D_SubCountry* list of first sub-country region used for further specification of country-level crop calendar data, original sub-country identification numbers and names according to GAUL dataset (Tab. 5.20);
- *CropCalendar(DataPreview&EXPORT)* select query set on *CropCalendar* table, helps with the crop management calendar data preview and export, metadata descrition of attribude field is given in design mode of table, use of select query is optiona (SQL code of query is given in APPENDIX 3);
- *CropShare(DataPreview&EXPORT)* select query set on *CropShare* and *D_ColRow30* tables, helps with the crop share data preview and export, use of select query is optiona (SQL code of query is given in APPENDIX 3);
- *ManureApplication(DataPreview&EXPORT)* select query set on *ManureApplication* and *D_ColRow30* tables, helps with the manure application rates data preview and export, use of select query is optiona (SQL code of query is given in APPENDIX 3);

Tab. 5.13: *CropCalendar data table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
COUNTRY	*Number(Integer)*	country code, numerical code by United Nations Statistics Division;
CrpCalSpec	*Number(Byte)*	identification number of sub-region for further specification of country level crop calendar;
CROP	*Text(4)*	code of original IFPRI crop and where appropriate IFPRI crop group (SWPY, BANP, OOIL, OPUL) replaced by country most frequent representative of the crop group;
OPER	*Text(50)*	identification of agro-technic operation;
YEA	*Number(Byte)*	year of crop cultivation;
DAY	*Number(Integer)*	number of day of agrotechnical operation (counted from 1.1. to 31.12., 29.2. not included);
DAT	*Date/Time*	date of agro technical operation (1.1. 2001 - 31.12.2005);
mHI	*Number(Byte)*	operation relevance for crop cultivated in high input management system (1 = relevant, 0 = not-relevant);
mIR	*Number(Byte)*	operation relevance for crop cultivated in irrigated high input management system (1 = relevant, 0 = not-relevant);
mLI	*Number(Byte)*	operation relevance for crop cultivated in low input management system (1 = relevant, 0 = not-relevant);
mSS	*Number(Byte)*	operation relevance for crop cultivated in subsistence management

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
		system (1 = relevant, 0 = not-relevant);

Tab. 5.14: *CropShare data table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
SimUID	*Number(LongInteger)*	SimU delineation (HRU*PX30*COUNTRY) zone number, can be used for display SimU delineation related data via spatial reference (land cover/land use data, crop management data);
MngSystem	*Text(2)*	identification of management system, HI - high input, LI - low input, IR - irrigated high input, SS - subsistence system, management systems according to You et Wood 2006;
HRU	*Number(Integer)*	homogenous response unit (HRU) code, assembled of the code of AltiClass (first character), SlpClass (second character) and SoilClass (third character), 88 - soil class = 88 (no-soil prevails);
Col_Row30	*Text(50)*	identification of 30' spatial resolution pixel (column and row number), counted from upper left corner;
COUNTRY	*Number(Integer)*	country code, numerical code by United Nations Statistics Division;
CrpCalSpec	*Number(Byte)*	identification number of sub-region for further specification of country level crop calendar;
CROP	*Text(4)*	code of original IFPRI crop and where appropriate IFPRI crop group (SWPY, BANP, OOIL, OPUL) replaced by country most frequent representative of the crop group;
CultType	*Number(Byte)*	crop cultivation type, crop classification according to duration of crop cultivation on the field, 1 (crops cultivated for < 365 days), 2 (crops cultivated for > 365 days);
RotType	*Number(Byte)*	crop rotation type, 1 (crops cultivated in monoculture), 2 (crops cultivated in rotation);
CrpArea	*Number(Double)*	SimU delineation specific physical area (ha) of particular crop;
SimUmask	*Number(Byte)*	SimU relevance mask (1 = relevant, 0 = not relevant), relevant if particular management system fulfills the area portion threshold (taken from land cover/land use statistic dataset);
absSimUmask	*Number(Byte)*	absolute SimU relevance mask (1 = relevant, 0 = not relevant), relevant only for one management system having the spatial dominance in the SimU delineation;
CropMask	*Number(Byte)*	crop relevance mask (1 = relevant, 0 = not relevant), relevant is crop having more than 5% area portion of the particular management system total area;
AltMask	*Number(Byte)*	alternative mask (1 = relevant, 0 = not-relevant), mark SimU relevant management alternative (rotation or monoculture1, monoculture2, monoculture n) which is spatially dominant in SimU delineation;

Tab. 5.15: *FertilizerApplication data table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
COUNTRY	*Number(Integer)*	country code, numerical code by United Nations Statistics Division;
CROP	*Text(4)*	code of original IFPRI crop and where appropriate IFPRI crop group (SWPY, BANP, OOIL, OPUL) replaced by country most frequent representative of the crop group;
N1_HiIr	*Number(Double)*	nitrogen (N) application 1 (kg/ha), before planting or during

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
		vegetation (perennial crops) together with P, K application, rainfed and irrigated high input management system, -999 no relevant (no area of corresponding management system in COUNTRY);
N2_HiIr	*Number(Double)*	nitrogen (N) application 2 (kg/ha), during vegetation, rainfed and irrigated high input management system, -999 no relevant (no area of corresponding management system in COUNTRY);
N3_HiIr	*Number(Double)*	nitrogen (N) application 3 (kg/ha), during vegetation (third year for selected crops), rain fed and irrigated high input management system, -999 no relevant (no area of corresponding management system in COUNTRY);
P_HiIr	*Number(Double)*	phosphorous (P2O5) application (kg/ha), before planting or during vegetation (perennial crops), rain fed and irrigated high input management system, -999 no relevant (no area of corresponding management system in COUNTRY);
K_HiIr	*Number(Double)*	potassium (K2O) application (kg/ha), before planting or during vegetation (perennial crops), rain fed and irrigated high input management system, -999 no relevant (no area of corresponding management system in COUNTRY);
N1_Li	*Number(Double)*	nitrogen (N) application 1 (kg/ha), before planting or during vegetation (perennial crops) together with P, K application, low input management system, -999 no relevant (no area of corresponding management system in COUNTRY);
N2_Li	*Number(Double)*	nitrogen (N) application 2 (kg/ha), during vegetation, low input management system, -999 no relevant (no area of corresponding management system in COUNTRY);
N3_Li	*Number(Double)*	nitrogen (N) application 3 (kg/ha), during vegetation (third year for selected crops), low input management system, -999 no relevant (no area of corresponding management system in COUNTRY);
P_Li	*Number(Double)*	phosphorous (P2O5) application (kg/ha), before planting or during vegetation (perennial crops), low input management system, -999 no relevant (no area of corresponding management system in COUNTRY);
K_Li	*Number(Double)*	potassium (K2O) application (kg/ha), before planting or during vegetation (perennial crops), low input management system, -999 no relevant (no area of corresponding management system in COUNTRY);
Flag1	*Number(Byte)*	metadata field, if = 1 then data was taken directly from original IFA country and crop specific dataset;
Flag2	*Number(Byte)*	metadata field, if = 1 then data was calculated from FAOSTAT dataset on country specific N, P, K consumption;
Flag3	*Number(Byte)*	metadata field, if = 1 then max. 90 kg/ha (rain fed and irrigated high input) or 45 kg/ha (low input management systems) application rates were arbitrary set for pulses, soya and groundnuts in case calculated value exceeded the threshold;

Tab. 5.16: *ManureApplication data table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
SimUID	*Number(LongInteger)*	SimU delineation (HRU*PX30*COUNTRY) zone number, can be used for display SimU delineation related data via spatial reference (land cover/land use data, crop management data);
HRU	*Number(Integer)*	homogenous response unit (HRU) code, assembled of the code of AltiClass (first character), SlpClass (second character) and SoilClass (third character), 88 - soil class = 88 (no-soil prevails);

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
Col_Row30	*Text(50)*	identification of 30' spatial resolution pixel (column and row number), counted from upper left corner;
COUNTRY	*Number(Integer)*	country code, numerical code by United Nations Statistics Division;
Nrate	*Number(Integer)*	nitrogen (kg/ha) coming from manure application, taken from high resolution global scale data (Liu et al. 2008);
Manure	*Number(LongInteger)*	total manure application (kg/ha), arbitrary set as Nrate/0,002;

Tab. 5.17: *CropIdentification data table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
CROP	*Text(4)*	code of original IFPRI crop and where appropriate IFPRI crop group (SWPY, BANP, OOIL, OPUL) replaced by country most frequent representative of the crop group;
CrpName	*Text(50)*	crop name;
Flag	*Number(Byte)*	metadata field, identification of crop source, 1 = original IFPRI data list of crops or crop groups, 2 = country specific representative for crop group;

Tab. 5.18: *CropRotationRules data table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
CROP	*Text(4)*	main crop, code of original IFPRI crop and where apropriate IFPRI crop group (SWPY, BANP, OOIL, OPUL) replaced by country most frequent representative of the crop group;
BARL	*Number(Byte)*	preceding crop, suitability for main crop: 0 = not suitable, 1 = not suitable but possible, 2 = suitable or very suitable;
BEAN	*Number(Byte)*	as above
CASS	*Number(Byte)*	as above
GROU	*Number(Byte)*	as above
MAIZ	*Number(Byte)*	as above
JUTE	*Number(Byte)*	as above
SUNF	*Number(Byte)*	as above
BHBE	*Number(Byte)*	as above
POTA	*Number(Byte)*	as above
RICE	*Number(Byte)*	as above
SORG	*Number(Byte)*	as above
SOYB	*Number(Byte)*	as above
SWTP	*Number(Byte)*	as above
WHEA	*Number(Byte)*	as above
SUGC	*Number(Byte)*	as above
COTT	*Number(Byte)*	as above
SUGB	*Number(Byte)*	as above
MILL	*Number(Byte)*	as above
MUST	*Number(Byte)*	as above
SESA	*Number(Byte)*	as above
SAFF	*Number(Byte)*	as above

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
RAPE	*Number(Byte)*	as above
PEAS	*Number(Byte)*	as above
MELO	*Number(Byte)*	as above
LINS	*Number(Byte)*	as above
LENT	*Number(Byte)*	as above
FLAX	*Number(Byte)*	as above
CPEA	*Number(Byte)*	as above
YAMS	*Number(Byte)*	as above
BANA	*Number(Byte)*	as above
PLAN	*Number(Byte)*	as above

Tab. 5.19: *CropDuration data table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
CROP	*Text(4)*	code of original IFPRI crop and where appropriate IFPRI crop group (SWPY, BANP, OOIL, OPUL) replaced by country most frequent representative of the crop group;
DURATION	*Number(Byte)*	duration (years) of crop cultivation;
LastYearRepeat	*Number(Byte)*	number of cultivation years after the last year indiced in crop calendar, the same calendar data as for the last year;

Tab. 5.20: *D_SubCountry domain table attribute fields descriptions.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
COUNTRY	*Number(Integer)*	country code, numerical code by United Nations Statistics Division;
GAUL1_code	*Number(LongInteger)*	identification of first sub-country region, GAUL administrative region code;
CrpCalSpec	*Number(Byte)*	identification number of sub-region for further specification of country level crop calendar;
NameCrpCalSpec	*Text(50)*	name of subregion for further specification of country level crop calendar;

5.5. Climate database (Climate_v10)

The data set provides the necessary climate input data (climate in the past and future climate scenarios). The climate database consists of two separate data sets:

- *HistoricalClimate_v10* is a MS Office Access 2003 database where the Tyndall weather data from 1901 to 2002 together with the monthly statistics derived from ECMWF database are stored. Six data tables hold the data (name specification is *ts_ cru_ts_2_10_1901_2002_<interval>_<variable-name>*) *_cld* (cloud cover in %), *_pre* (precipitation in mm), *_rad* (radiation in MJ/m²), *_tmn* (near-surface temperature minimum in °C), *_tmx* (near-surface temperature maximum in °C), and *_wet* (wet day frequency in days) separately for 10, 25, 50, and 100 year intervals. Seven tables contain the statistical values *sd_tmin* (standard deviation of minimum temperature), *sd_tmax* (standard deviation of maximum temperature), *sd_rain* (standard deviation of precipitation), *sk_rain* (skewness of precipitation), *ww_rain* (probabilities of wet day after wet day) and *dw_rain* (probabilities of wet day after dry day). All tables have the same structure, described in Tab. 5.21;

- Eight Tyndall climate change scenarios are available as postgreSQL databases. The database backups comprise the PCM and HadCM3 scenarios for the 4 different global warming values A1FI, A2, B1 and B2. Each backup file contains seven tables (name specification is: *scenario_<global-climate-model>_<variable-name>*): *_cld* (cloud cover in %), *_pre* (precipitation in mm), *_rad* (radiation in MJ/m²), *_tmn* (near-surface temperature minimum in °C), *_tmx* (near-surface temperature maximum in °C), *_tmp* (near-surface temperature in °C), and *_wet* (wet day frequency in days). All tables have the same structure, described in Tab. 5.22.

Tab. 5.21: *HistoticalClimate_v10 structure of tables and identification of attribute fields.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
period	*Number(Integer)*	time interval (years) for the average value of the Tyndall dataset;
lon	*Number(single)*	longitude of 0.5° (Tyndall) or 2.5° (ECWMF) spatial resolution pixel, pixel identification;
lat	*Number(single)*	latitude of 0.5° (Tyndall) or 2.5° (ECWMF) spatial resolution pixel, pixel identification;
jan	*Number(single)*	mean value for January, depends on the table theme;
feb	*Number(single)*	mean value for February, depends on the table theme;
mar	*Number(single)*	mean value for March, depends on the table theme;
april	*Number(Single)*	mean value for April, depends on the table theme;
may	*Number(single)*	mean value for May, depends on the table theme;
jun	*Number(single)*	mean value for June, depends on the table theme;
jul	*Number(single)*	mean value for July, depends on the table theme;
aug	*Number(single)*	mean value for August, depends on the table theme;
sep	*Number(single)*	mean value for September, depends on the table theme;
oct	*Number(single)*	mean value for October, depends on the table theme;
nov	*Number(single)*	mean value for November, depends on the table theme;
dec	*Number(single)*	mean value for December, depends on the table theme;

Tab. 5.22: *ClimateScenarios backups table structure and identification of attribute fields.*

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
year	*Number(LongInteger)*	year, range 1 (2001) – 100 (2100);
lon	*Number(single)*	longitude of 0.5° spatial resolution pixel, pixel identification;
lat	*Number(single)*	latitude of 0.5° spatial resolution pixel, pixel identification;
jan	*Number(single)*	mean value for January, depends on the table theme;
feb	*Number(single)*	mean value for February, depends on the table theme;
mar	*Number(single)*	mean value for March, depends on the table theme;
april	*Number(Single)*	mean value for April, depends on the table theme;
may	*Number(single)*	mean value for May, depends on the table theme;
jun	*Number(single)*	mean value for June, depends on the table theme;
jul	*Number(single)*	mean value for July, depends on the table theme;
aug	*Number(single)*	mean value for August, depends on the table theme;

ATTRIBUTE FIELD	DATA TYPE	DESCRIPTION
sep	*Number(single)*	mean value for September, depends on the table theme;
oct	*Number(single)*	mean value for October, depends on the table theme;
nov	*Number(single)*	mean value for November, depends on the table theme;
dec	*Number(single)*	mean value for December, depends on the table theme;

References

Adams, D.M.; Alig, R.J.; Callaway, J.M.; McCarl, B.A.; Winnett, S.M., 1996. The forest and agricultural sector optimization model (FASOM): model structure and policy applications. Res. Pap. PNW-RP-495. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 60 p.

Balkovič, J., Schmid, E., Bujnovský, R., Skalský, R., Poltárska, K., 2006. Biophysical modelling for evaluating soil carbon sequestration potentials on arable land in the pilot area Baden-Württemberg (Germany). Agriculture, Vol. 52, No. 4, pp. 169 – 176

Batjes, N.H. (Ed.), 1995. A homogenized soil data file for globalenvironmental research: a subset of FAO. ISRIC and NRCS profiles(Version 1.0). Working Paper and Preprint 95/10b. ISRIC - World Soil Information, Wageningen, 43 p. Available on internet: <http://www.isric.org/ISRIC/WebDocs/Docs/isric_wp95_10.pdf>, Accessed: February 27 2008

Batjes, N., H., 2006. ISRIC-WISE derived soil properties on a 5 by 5 arc-minutes global grid (ver. 1.1). Report 2006/2, ISRIC - World Soil Information, Wageningen, 46 pp., Available on internet: http://www.isric.org/isric/webdocs/Docs/ISRIC_Report_2006_02.pdf, Accessed: February 8, 2008

Batjes, N. H., Bridges, E.M., Nachtergaele, F.O., 1995. World Inventory of Soil Emission Potentials: Development of a Global Soil Data Base of Process-Controlling Factors. In Peng, S., Ingram, K.T., Neue, H.U., Ziska, L.H. (Eds.) 1995. Climate change and rice. Springer-Verlar, Berlin, Heidelberg, p. 102 – 115

Boogaart, H.L., Van Diepen, C.A., Rotter, R.P., Cabrera, J.M., Van Laar, H.H., 1998: User´s guide for the WOFOST 7.1 crop growth simulation model and WOFOST Control Center 1.5. Technical document. DLO Winand Staring Centre, Wageningen, 141 p.

Di Gregorio, A., Jansen, L., 2000. Land cover classification system, classification concepts and user manual. FAO, Rome, Available on internet: <http://www.fao.org/docrep/003/X0596E/X0596E00.HTM>, Accessed: February 14 2008

Dobos, E., 2006. Albedo. In Lal, R. (Ed.). Encyclopedia of Soil Science – Second edition, Volume 1. Taylor&Franciss CRC Press, New York, (2006), pp. 63 – 65

Driessen, P., Deckers, J., Spaargaren, O., Nachtergaele, F. 2001. Lecture notes on the major soils of the world. World Soil Resources Reports 94, FAO, Rome, 334 p.

FAO, 1959a. World crop harvest calendar for sugar beets. Meeting of Experts of Time Reference (7 – 18 Dec.). FAO, Roma, 6 p.

FAO, 1959b. World crop harvest calendar for sugar cane. Meeting of Experts of Time Reference (7 – 18 Dec.). FAO, Roma, 7 p.

FAO, 1959c. World crop harvest calendar for coffee. Meeting of Experts of Time Reference (7 – 18 Dec.). FAO, Roma, 7 p.

FAO-UNESCO, 1974. Soil map of the world, Volume 1 - Legend. Unesco, Paris, 59 p.

Fischer, G., van Velthuizen, H., Nachtergele, F., 2000. Global Agro-Ecological Zones Assessment: Methodology and Results. Interim Report IR-00-064, IIASA, Laxenburg, 48 p., Available on internet: <http://www.iiasa.ac.at/Admin/PUB/Documents/RR-02-002.pdf>, Acessed: February 14 2008

IFA, 1992. World Fertilizer Use Manual. Germany, 1992. 632 p. ISBN 2-9506299-0-3.

Jurášek, P., 1997. World Agriculture. Part I. (in Slovak). AT Publishing, Bratislava, 263 p. ISBN 80-967812-0-0.

Jurášek, P., 1998. World Agriculture. Part II. (in Slovak). AT Publishing, Bratislava, 387 s. ISBN 80-967812-9-4.

Justice C.O. and Becker-Reshef I.(Eds.) (2007) Report from the Workshop on Developing a Strategy for Global Agricultural Monitoring in the framework of Group on Earth Observations (GEO), UN FAO, July 2007, Geography Dept., University of Maryland, 66, pp, Available on internet: <ftp://ftp.iluci.org/GEO_Ag> , Accessed: February 6, 2008

Kučera, L., Genovese, G., (Eds.), 2004a. Crop Monographies on Central European Countries. Vol. 2 Estonia, Latvia, Lithuania, Poland. Office for Official Publications of the European Communities, Luxembourg, 122 pp. ISBN 92-894-8177-3. Available on internet: (http://agrifish.jrc.it/marsstat/Crop_Yield_Forecasting/MOCA/00000000.HTM) Accessed: March 11, 2008.

Kučera, L., Genovese, G., (Eds.), 2004b. Crop Monographies on Central European Countries. Vol. 3 Czech Republic, Slovakia, Hungary, Slovenia. Office for Official Publications of the European Communities, Luxembourg, 160 pp. ISBN 92-894-8178-1. Available on internet: (http://agrifish.jrc.it/marsstat/Crop_Yield_Forecasting/MOCA/00000000.HTM) Accessed: March 11, 2008.

Kučera, L., Genovese, G., (Eds.), 2004c. Crop Monographies on Central European Countries. Vol. 4 Romania, Bulgaria, Turkey. Office for Official Publications of the European Communities, Luxembourg, 122 pp. ISBN 92-894-8179-X. Available on internet: (http://agrifish.jrc.it/marsstat/Crop_Yield_Forecasting/MOCA/00000000.HTM) Accessed: March 11, 2008.

Lethcoe, K.J., Klaver, R.W., 1998. Simulating the Interrupted Goode Homolosine Projection With ArcInfo. 18th Annual ESRI International User Conference in San Diego Proceedings, California, Available on internet: <http://gis.esri.com/library/userconf/proc98/PROCEED.HTM>, Accessed: February 12, 2008

Liu J., You L., Obersteiner M., Zehnder A.J.B. and Yang, H., 2008. A high-resolution assessment on global nitrogen flows in cropland. In preparation.

MacKerron, D. K. L., 1992. Agrometeorological Aspects of Forecasting Yields of Potato within the E. C. Office for Official Publications of the European Communities, Luxembourg, 250 pp. ISBN 92-826-3538-4.

Mitchell, T. D., Carter, T. R., Jones, P. D., Hulme, M., New, M., 2004. A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901-2000) and 16 scenarios (2001-2100). Tyndall Centre for Climate Change Research Working Paper 55. 25 p., Available on Internet: http://www.tyndall.ac.uk/publications/working_papers/wp55.pdf, Accessed: March 14, 2008

Narciso, G., Ragni, P., Venturi, A., 1992. Agro-meteorological aspects of crops in Italy, Spain and Greece: A summary review for common and durum wheat, barley, maize, rice, sugar beet, sunflower, soya bean, rape, potato, tobacco, cotton, olive and grape crops. Office for Official Publications of the European Communities, Luxembourg, 440 pp. ISBN 92-826-3995-6.

Rivington, M., Matthews, K.B., Buchan, K., 2002. A Comparison of Methods for Providing Solar Radiation Data to Crop Models and Decision Support Systems. In Rizzoli, A.E., Jakeman, J.J., (Eds.) Integrated Assessment and Decision Support, Proceedings of the 1st Biennial Meeting of the iEMSs, Volume 3, The International Environmental Modelling and Software Society, Lugano, Switzerland, pp. 193 – 198, Available on Internet: http://www.wcai-infonet.org/servlet/BinaryDownloaderServlet?filename=1065620840070_wdds25.pdf&refID=113918, Accessed: March 14, 2008

Rossiter, D. G. 2003. Biophysical models in land evaluation. In Encyclopedia of Life Support Systems (EOLSS), 2003, 16 p. Available on internet: <www.itc.nl/~rossiter/Docs/EOLSS_1527_Preprint.pdf >, Accessed: February 7, 2008

Russell, G., 1990. Barley Knowledge Base. Office for Official Publications of the European Communities, Luxembourg, 142 pp. ISBN 92-826-1647-9.
Russell, G., Wilson, G. W., 1994. An Agro-Pedo-Climatological Knowledge-Base of Wheat in Europe. Office for Official Publications of the European Communities, Luxembourg, 160 pp. CL-NA-15789-EN-C.
Schmid, E., Balkovič, J., Moltchanova E., Skalský, R., Poltárska, K., Müller, B., Bujnovský, R., 2006: Biophysical process modeling for EU25: concept, data, methods, and results. Deliverable D3 (T30), Final Report, Appendix II., EU FP 6 Project INSEA – Integrated Sink Enhancement Assessment (SSPI-CT-2003/503614 with DG RTD), 2006, 76 p.
Schaap, M.G., Bouten, W., 1996. Modelling Water Retention Curves of Sandy Soils Using Neural Networks. Water Resour. Res., Vol. 32, s. 3033 – 3040.
Siebert, S., Döll, P., Feick, S., Hoogeveen, J., Frenken, K., 2007. Global Map of Irrigation Areas version 4.0.1. Johann Wolfgang Goethe University, Frankfurt an Main, Germany/ FAO, Rome. Available on internet: (http://www.fao.org/nr/water/aquastat/irrigationmap/index10.stm). Accessed: March 11 2008.
Stolbovoy, V., Montanarella, L., Panagos, P., (Eds.) 2007. Carbon Sink Enhancement in Soils of Europe: Data, Modeling, Verification. JRC technical and scientific reports, EUR 23037 EN, Office for Official Publications of the European Communities, Luxembourg, 183 p. Available on internet: <http://eusoils.jrc.it/ESDB_Archive/eusoils_docs/other/EUR23037.pdf>, Acessed: February 27, 2008
USDA, 1994. Major World Crop Areas and Climatic Profiles. World Agricultural Outlook Board, U. S. Department of Agriculture. Agriculture Handbook No. 664., 279 p.
USDA-NRCS, 2007. Hydrologic Soil Groups. National Engineering Handbook : Part 630 Hydrology : Chapter 7. 210-VI-NEH-630.7, USDA, Washington DC. Available on internet: <http://directives.sc.egov.usda.gov/media/pdf/H_210_630_7.pdf>, Accessed February 21 2008
Williams, J.R. 1995. The EPIC Model. In Computer Models of Watershed Hydrology (Ed.: V.P. Singh). Water Resources Publications, Highlands Ranch, Colorado, 1995, pp 909-1000.
Wösten, J. H. M., Van Genuchten, M. T., 1988. Using Texture and Other Soil Properties to Predict the Unsaturated Soil Hydraulic Functions. Soil. Sci. Soc. Am. J., Vol. 52, p. 1762 - 1770
You, L. and S. Wood. 2006. An entropy approach to spatial disaggregation of agricultural production. Agricultural Systems Vol.90, Issues1-3 p.329-347.

Appendix 1: Input data requirements of the EPIC model

Data on four major input data components: weather, soil, topography and management practices is essential to run EPIC.

The **weather variables** necessary for running EPIC are precipitation (in mm), minimum and maximum air temperature (in degree Celsius), and solar radiation (in MJ/m^2). If the Penman methods are used to estimate potential evapo-transpiration, wind speed (in m/sec measured at 10 m height), and relative humidity (in %) are also required. If measured daily weather data is available it can be directly input into EPIC. In addition, monthly statistics of this daily weather (mean, standard deviation, skew coefficient, probabilities of wet-dry and wet-wet days, etc.) need to be computed and input in the model. EPIC provides a statistical support program to compute the statistics of relevant variables based on daily weather records. Consequently, long historical daily weather records (20-30 years) for all weather variables are desirable for statistical parameter calculations. Based on the weather variable statistics, EPIC can generate weather patterns for long-run analyses (100+ years), or as indicated above, daily weather records (e.g., from world climate models with downscaling procedures) can be input directly. There is also the option of reading a sequence of actual daily weather and use generated weather afterwards or before within a simulation run.

The **topography** of a field or HRU is described by average field size (ha), slope length (m), and slope (%). In addition, elevation, longitude and latitude are needed for each site or HRU. Information on elevation, longitude and latitude is usually provided by a climate station of a digital elevation map.

A large number of physical and chemical **soil parameters** to describe each soil layer and subsequently an entire soil profile can be input in EPIC. These soil parameters (Tab.1) are separated between general and layer-specific as well as between essential and useful soil information requirement. The essential soil parameters are mandatory input while the remaining ones would help to further describe a soil specific profile situation. In EPIC, a soil profile can be split in up to 10 soil layers of which each is described by a specific set of chemical and physical soil parameters. If, for instance, the description of only two soil layers is available (top-soil and sub-soil), EPIC still allows (optional) to split the soil profile into ten soil layers. It assures that e.g., soil temperature and soil moisture can be appropriately estimated through soil layers and time.

Wide range of **management scheduling** in EPIC allows flexibility in modelling different cropping, forestation, and tillage systems (including crop rotations and crop mixes). However, it requires reliable information of the actual management practice for a given region or site. Generally, information on:

- Date of planting (including potential heat units the crop needs to reach maturity);
- Date, type (commercial; dairy, swine, etc. manure), and amount of fertilizer (elemental NPK) in kg/ha; if manure is applied, information on application rate (in case of grazing the stocking rate) and nutrient composition (orgN, minN (NO3-N + NH3-N), orgP, minP, minK, orgC, and fraction of NH3-N on minN) is needed;
- Date and amount of irrigation (including NO_3 and salt concentration in irrigation water) in mm;
- Date and type of tillage operation (plough, harrow spike, field cultivator, thinning, etc.); and
- Date and type of harvesting (combine, hay cutting, grazing, etc.) is needed.

Table 1: *List of physical and chemical soil parameters needed by EPIC*

ESSENTIAL SOIL INFORMATION	USEFUL SOIL INFORMATION
general soil and hydrologic information	
soil albedo (moist)	initial soil water content (fraction of field capacity)
hydrologic soil group (A, B, C, or D)	minimum depth to water table in m
	maximum depth to water table in m
	initial depth to water table in m
	initial ground water storage in mm
	maximum ground water storage in mm
	ground water residence time in days
	return flow fraction of water percolating through root
	soil weathering (CaCO3 soils; non-CaCO3 soils that
	number of years of cultivation
	soil group (kaolinitic, mixed, or smetitic)
	fraction of org C in biomass pool
	fraction of humus in passive pool
	soil weathering code
by soil layer	
depth from surface to bottom of soil layer in m	bulk density of the soil layer (oven dry) in t/m3
bulk density of the soil layer (moist) in t/m3	wilting point (1500 kPa for many soils) in m/m
sand content in %	field capacity (33 kPA for many soils) in m/m
silt content in %	Initial organic N concentration in g/t
soil pH	sum of bases in cmol/kg
organic carbon in %	cation exchange capacity in cmol/kg
calcium carbonate content in %	coarse fragment content in %vol.
	initial soluble N concentration in g/t
	initial soluble P concentration in g/t
	initial organic P concentration in g/t
	exchangeable K concentration in g/t
	crop residue in t/ha
	saturated conductivity in mm/h
	fraction of storage interacting with NO3 leaching
	phosphorous sorption ratio
	lateral hydraulic conductivity in mm/h
	electrical conductivity in mm/cm
	structural litter kg/ha
	metabolic litter kg/ha
	lignin content of structural litter in kg/ha
	carbon content of structural litter in kg/ha
	C content of metabolic litter in kg/ha
	C content of lignin of structural litter in kg/ha
	N content of lignin of structural litter in kg/ha
	C content of biomass in kg/ha
	C content of slow humus in kg/ha
	C content of passive humus kg/ha
	N content of structural litter in kg/ha
	N content of metabolic litter in kg/ha
	N content of biomass in kg/ha
	N content of slow humus in kg/ha
	N content of passive humus in kg/ha
	observed C content at the end of simulation

Appendix 2: Selected sources of national crop calendar data

COUNTRY	SOURCE
Afghanistan	*http://www.icarda.org/afghanistan/NA/Full/Primary_F.htm*
Angola	*http://www.fao.org/docrep/009/j8081e/j8081e00.htm*
Australia	*http://151.121.3.140/remote/aus_sas/crop_information/calendars/index_of_clndrs.htm*
Bangladesh	*http://151.121.3.140/remote/aus_sas/crop_information/calendars/index_of_clndrs.htm*
Burkina Faso	*http://v4.fews.net/docs/Publications/**Burkina**_200704en.pdf*
Canada	*http://www.fas.usda.gov/remote/canada/index.htm*
Côte d´Ivoire	*http://www.fas.usda.gov/pecad2/highlights/2002/09/West_Africa/pictures/ic_cropcalendar.htm*
Ethiopia	*http://www.fas.usda.gov/pecad2/highlights/2002/10/ethiopia/baseline/Eth_Crop_Calendar.htm*
India	*http://151.121.3.140/remote/aus_sas/crop_information/calendars/index_of_clndrs.htm*
Iran	*http://www.fas.usda.gov/remote/mideast_pecad/iran/iran.htm*
Iraq	*www.nationalaglawcenter.org/assets/crs/RL32093.pdf*
Kazakhstan	*http://www.fas.usda.gov/pecad2/highlights/2005/03/Kazakh_Ag/crop_cal.htm*
Kenya	*http://www.fas.usda.gov/pecad/highlights/2004/12/Kenya/images/crop_calendar.htm*
Madagascar	*http://www.wildmadagascar.org/maps/crops.html*
Malawi	*http://v4.fews.net/docs/Publications/South_**2007**10en.pdf*
Mali	*http://v4.fews.net/docs/Publications/**Mali**_**2006**12en.pdf*
Mozambique	*http://v4.fews.net/docs/Publications/**Mozambique**_**2006**07en.pdf*
Nicaragua	*http://usda.gov/pecad2/articles/99-03/nic0399.pdf*
Nigeria	*www.fas.usda.gov/pecad2/highlights/2002/03/**nigeria**/pictures/**crop_calendar_nigeria**.pdf*
Russian Federation	*http://www.fas.usda.gov/remote/soviet/Crop_Calendars_2004/rs_districts.htm*
Rwanda	*www.fews.net/centers/files/**Rwanda**_**2000**09en.pdf*
Sudan	*http://www.sudan.net/statistic/sudancal.html*
Tanzania	*http://www.fas.usda.gov/pecad2/highlights/2003/03/tanzania/images/crop_calendar.htm*
Turkey	*http://www.fas.usda.gov/remote/mideast_pecad/turkey/turkey.htm*
Zambia	*http://v4.fews.net/docs/Publications/Zambia_200705en.pdf*
Zimbabwe	*http://www.fas.usda.gov/pecad2/highlights/2004/06/zimbabwe/images/zimbabwe_cropcalendar.htm*
Viet Nam	*www.cimmyt.org/english/docs/**maize**_producsys/**vietnam**.pdf*
Uganda	*www.foodnet.cgiar.org/inform/Fews/**fews00may**.pdf*

Appendix 3: SQL codes of select queries for preview and export the data

1. SQL code of *SpatialReference(DataPreview&EXPORT)* select query:

SELECT SpatialReference.Col_Row, SpatialReference.XCOORD, SpatialReference.YCOORD, SpatialReference.ZoneID, SpatialReference.SimUID, SpatialReference.mCrpLnd, SpatialReference.mCrpLnd_H, SpatialReference.mCrpLnd_L, SpatialReference.mCrpLnd_I, SpatialReference.mCrpLnd_S, SpatialReference.mOthAgri, SpatialReference.mGrass, SpatialReference.mForest, SpatialReference.mWetLnd, SpatialReference.mOthNatLnd, SpatialReference.mNotRel
FROM SpatialReference;

2. SQL code of *SimUstatistics(DataPreview&EXPORT)* select query:

SELECT SimUstatistics.SimUID, SimUstatistics.HRU, D_ColRow30.Col30, D_ColRow30.Row30, SimUstatistics.COUNTRY, SimUstatistics.SimUArea, SimUstatistics.CrpLnd, SimUstatistics.CrpLnd_H, SimUstatistics.CrpLnd_L, SimUstatistics.CrpLnd_I, SimUstatistics.CrpLnd_S, SimUstatistics.OthAgri, SimUstatistics.Grass, SimUstatistics.Forest, SimUstatistics.WetLnd, SimUstatistics.OthNatLnd, SimUstatistics.NotRel, SimUstatistics.mCrpLnd, SimUstatistics.mCrpLnd_H, SimUstatistics.mCrpLnd_L, SimUstatistics.mCrpLnd_I, SimUstatistics.mCrpLnd_S, SimUstatistics.mOthAgri, SimUstatistics.mGrass, SimUstatistics.mForest, SimUstatistics.mWetLnd, SimUstatistics.mOthNatLnd, SimUstatistics.mNotRel
FROM SimUstatistics, D_ColRow30
WHERE (((SimUstatistics.Col_Row30)=[d_colrow30].[col_row30]))
ORDER BY SimUstatistics.SimUID;

3. SQL code of *Topo&Soil_MineralSoil(DataPreview&EXPORT)* select query:

SELECT ZoneData.Zone_ID, ZoneData.HRU, D_ColRow30.Col30, D_ColRow30.Row30, ZoneData.ZoneLon, ZoneData.ZoneLat, ZoneData.ZoneAlti, ZoneData.ZoneSlp, SoilAnal_MineralSoil.HG, SoilAnal_MineralSoil.ALB, SoilAnal_MineralSoil.DEPTH1, SoilAnal_MineralSoil.DEPTH2, SoilAnal_MineralSoil.DEPTH3, SoilAnal_MineralSoil.DEPTH4, SoilAnal_MineralSoil.DEPTH5, SoilAnal_MineralSoil.VS1, SoilAnal_MineralSoil.VS2, SoilAnal_MineralSoil.VS3, SoilAnal_MineralSoil.VS4, SoilAnal_MineralSoil.VS5, SoilAnal_MineralSoil.SAND1, SoilAnal_MineralSoil.SAND2, SoilAnal_MineralSoil.SAND3, SoilAnal_MineralSoil.SAND4, SoilAnal_MineralSoil.SAND5, SoilAnal_MineralSoil.SILT1, SoilAnal_MineralSoil.SILT2, SoilAnal_MineralSoil.SILT3, SoilAnal_MineralSoil.SILT4, SoilAnal_MineralSoil.SILT5, SoilAnal_MineralSoil.CLAY1, SoilAnal_MineralSoil.CLAY2, SoilAnal_MineralSoil.CLAY3, SoilAnal_MineralSoil.CLAY4, SoilAnal_MineralSoil.CLAY5, SoilAnal_MineralSoil.BD1, SoilAnal_MineralSoil.BD2, SoilAnal_MineralSoil.BD3, SoilAnal_MineralSoil.BD4, SoilAnal_MineralSoil.BD5, SoilAnal_MineralSoil.CEC1, SoilAnal_MineralSoil.CEC2, SoilAnal_MineralSoil.CEC3, SoilAnal_MineralSoil.CEC4, SoilAnal_MineralSoil.CEC5, SoilAnal_MineralSoil.SB1, SoilAnal_MineralSoil.SB2, SoilAnal_MineralSoil.SB3, SoilAnal_MineralSoil.SB4, SoilAnal_MineralSoil.SB5, SoilAnal_MineralSoil.PH1, SoilAnal_MineralSoil.PH2, SoilAnal_MineralSoil.PH3, SoilAnal_MineralSoil.PH4, SoilAnal_MineralSoil.PH5, SoilAnal_MineralSoil.CARB1, SoilAnal_MineralSoil.CARB2, SoilAnal_MineralSoil.CARB3, SoilAnal_MineralSoil.CARB4, SoilAnal_MineralSoil.CARB5, SoilAnal_MineralSoil.CORG1, SoilAnal_MineralSoil.CORG2, SoilAnal_MineralSoil.CORG3, SoilAnal_MineralSoil.CORG4, SoilAnal_MineralSoil.CORG5, SoilAnal_MineralSoil.FWC1, SoilAnal_MineralSoil.FWC2, SoilAnal_MineralSoil.FWC3, SoilAnal_MineralSoil.FWC4, SoilAnal_MineralSoil.FWC5, SoilAnal_MineralSoil.WP1, SoilAnal_MineralSoil.WP2, SoilAnal_MineralSoil.WP3, SoilAnal_MineralSoil.WP4, SoilAnal_MineralSoil.WP5, SoilAnal_MineralSoil.KS1, SoilAnal_MineralSoil.KS2, SoilAnal_MineralSoil.KS3, SoilAnal_MineralSoil.KS4, SoilAnal_MineralSoil.KS5, ClimateReference.Tyndall_X, ClimateReference.Tyndall_Y
FROM ZoneData, SoilAnal_MineralSoil, ClimateReference, D_ColRow30
WHERE (((SoilAnal_MineralSoil.ZoneSTU)=[zonedata].[zonestu]) AND ((ClimateReference.Col_Row30)=[zonedata].[col_row30]) AND ((D_ColRow30.Col_Row30)=[zonedata].[col_row30]))
ORDER BY ZoneData.Zone_ID;

4. SQL code of *Topo&Soil_OrganicSoil(DataPreview&EXPORT)* select query:

SELECT ZoneData.Zone_ID, ZoneData.HRU, D_ColRow30.Col30, D_ColRow30.Row30, ZoneData.ZoneLon, ZoneData.ZoneLat, ZoneData.ZoneAlti, ZoneData.ZoneSlp, SoilAnal_OrganicSoil.HG, SoilAnal_OrganicSoil.ALB, SoilAnal_OrganicSoil.DEPTH1, SoilAnal_OrganicSoil.DEPTH2, SoilAnal_OrganicSoil.DEPTH3, SoilAnal_OrganicSoil.DEPTH4, SoilAnal_OrganicSoil.DEPTH5, SoilAnal_OrganicSoil.VS1, SoilAnal_OrganicSoil.VS2, SoilAnal_OrganicSoil.VS3, SoilAnal_OrganicSoil.VS4, SoilAnal_OrganicSoil.VS5, SoilAnal_OrganicSoil.SAND1, SoilAnal_OrganicSoil.SAND2, SoilAnal_OrganicSoil.SAND3, SoilAnal_OrganicSoil.SAND4, SoilAnal_OrganicSoil.SAND5, SoilAnal_OrganicSoil.SILT1, SoilAnal_OrganicSoil.SILT2, SoilAnal_OrganicSoil.SILT3, SoilAnal_OrganicSoil.SILT4, SoilAnal_OrganicSoil.SILT5, SoilAnal_OrganicSoil.CLAY1, SoilAnal_OrganicSoil.CLAY2, SoilAnal_OrganicSoil.CLAY3, SoilAnal_OrganicSoil.CLAY4, SoilAnal_OrganicSoil.CLAY5, SoilAnal_OrganicSoil.BD1, SoilAnal_OrganicSoil.BD2, SoilAnal_OrganicSoil.BD3, SoilAnal_OrganicSoil.BD4, SoilAnal_OrganicSoil.BD5, SoilAnal_OrganicSoil.CEC1, SoilAnal_OrganicSoil.CEC2, SoilAnal_OrganicSoil.CEC3, SoilAnal_OrganicSoil.CEC4, SoilAnal_OrganicSoil.CEC5, SoilAnal_OrganicSoil.SB1, SoilAnal_OrganicSoil.SB2, SoilAnal_OrganicSoil.SB3, SoilAnal_OrganicSoil.SB4, SoilAnal_OrganicSoil.SB5, SoilAnal_OrganicSoil.PH1, SoilAnal_OrganicSoil.PH2, SoilAnal_OrganicSoil.PH3, SoilAnal_OrganicSoil.PH4, SoilAnal_OrganicSoil.PH5, SoilAnal_OrganicSoil.CARB1, SoilAnal_OrganicSoil.CARB2, SoilAnal_OrganicSoil.CARB3, SoilAnal_OrganicSoil.CARB4, SoilAnal_OrganicSoil.CARB5, SoilAnal_OrganicSoil.CORG1, SoilAnal_OrganicSoil.CORG2, SoilAnal_OrganicSoil.CORG3, SoilAnal_OrganicSoil.CORG4, SoilAnal_OrganicSoil.CORG5, SoilAnal_OrganicSoil.FWC1, SoilAnal_OrganicSoil.FWC2, SoilAnal_OrganicSoil.FWC3, SoilAnal_OrganicSoil.FWC4, SoilAnal_OrganicSoil.FWC5, SoilAnal_OrganicSoil.WP1, SoilAnal_OrganicSoil.WP2, SoilAnal_OrganicSoil.WP3, SoilAnal_OrganicSoil.WP4, SoilAnal_OrganicSoil.WP5, SoilAnal_OrganicSoil.KS1, SoilAnal_OrganicSoil.KS2, SoilAnal_OrganicSoil.KS3, SoilAnal_OrganicSoil.KS4, SoilAnal_OrganicSoil.KS5, ClimateReference.Tyndall_X, ClimateReference.Tyndall_Y
FROM ZoneData, SoilAnal_OrganicSoil, ClimateReference, D_ColRow30
WHERE (((SoilAnal_OrganicSoil.ZoneSTU)=[zonedata].[zonestu]) AND ((ClimateReference.Col_Row30)=[zonedata].[col_row30]) AND ((D_ColRow30.Col_Row30)=[ZoneData].[Col_Row30]))
ORDER BY ZoneData.Zone_ID;

5. SQL code of *CropCalendar(DataPreview&EXPORT)* select query:

SELECT CropCalendar.COUNTRY, CropCalendar.CROP, CropCalendar.CrpCalSpec, CropCalendar.OPER, CropCalendar.YEA, CropCalendar.DAY, CropCalendar.DAT, CropCalendar.mHI, CropCalendar.mIR, CropCalendar.mLI, CropCalendar.mSS
FROM CropCalendar
ORDER BY CropCalendar.COUNTRY, CropCalendar.CROP, CropCalendar.CrpCalSpec, CropCalendar.DAT;

6. SQL code of *CropShare(DataPreview&EXPORT)* select query:

SELECT CropShare.SimUID, D_ColRow30.Col30, D_ColRow30.Row30, CropShare.CrpCalSpec, CropShare.CROP, CropShare.CultType, CropShare.RotType, CropShare.CrpArea, CropShare.SimUmask, CropShare.absSimUmask, CropShare.CropMask, CropShare.AltMask, CropShare.MngSystem
FROM CropShare, D_ColRow30
WHERE (((CropShare.MngSystem)="HI") AND ((CropShare.Col_Row30)=[d_colrow30].[col_row30]))
ORDER BY CropShare.SimUID;

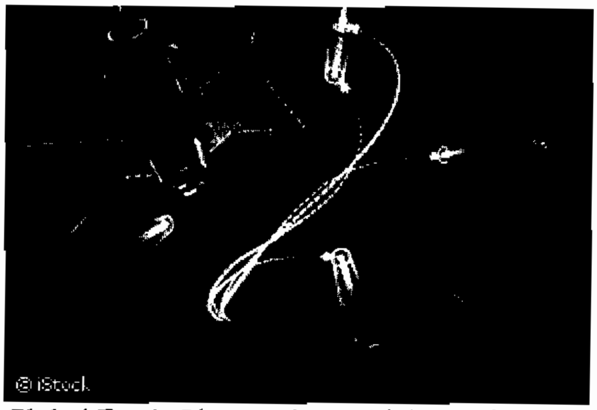
7. SQL code of *ManureApplication(DataPreview&EXPORT)* select query:

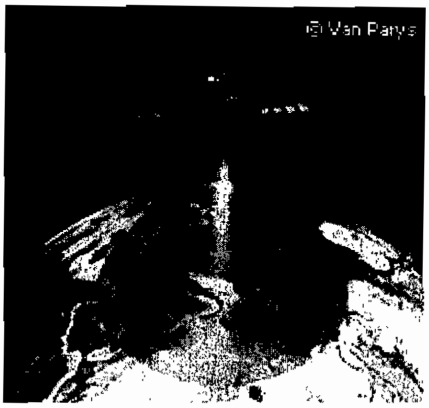
SELECT ManureApplication.SimUID, ManureApplication.HRU, D_ColRow30.Col30, D_ColRow30.Row30, ManureApplication.COUNTRY, ManureApplication.Nrate, ManureApplication.Manure
FROM ManureApplication, D_ColRow30

WHERE (((D_ColRow30.Col_Row30)=[manureapplication].[col_row30]))
ORDER BY ManureApplication.HRU;

Global Earth Observation – a new tool for sustainable development

GEO-BENE





Global Earth Observation, which provides a comprehensive overview of what is happening in the environment, offers important benefits in a wide range of areas. For example, in agriculture it can help agri-business boost yields by spotting where fertiliser needs to be applied. Now the GEO-BENE (Global Earth Observation – Benefit Estimation: Now, Next and Emerging) project is carrying out the world's first systematic study of the benefits of Global Earth Observation.

GEO-BENE brings together 12 partners from 5 EU countries plus Switzerland, South Africa and Japan with the aim of developing methods and tools designed to clarify the economic and soeial benefits of Global Earth Observation. From this, policies can be defined to support the implementation of international agreements on sustainable development in a range of fields.

The project covers nine areas: disasters, health, energy, climate, water, weather, ecosystems, agriculture, and biodiversity.

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Getting the better of the weather

Even with current technology, we still cannot provide completely accurate weather forecasts, and every year many people die and vast amounts of money are spent as a result. Being able to provide reliable weather forecasts would be a huge advantage for almost every European industry. GEO-BENE researchers have investigated the impact of climate change on weather and crop yields in the future, and developed a tool to quantify the value of weather-related satellite information.

Cherishing biodiversity

Global Earth Observation is also a useful tool to survey biodiversity and protect our ecosystems. Ecosystems form the basis of life on Earth; they provide us with food, air, water and energy. But they have been under threat for a number of years from pollution, climate change and intensive agricultural methods. Global Earth Observation can give us state-of-the-art information about the current condition of ecosystems around the world in order to promote sustainability and good resource management.

GEO-BENE has focused on the creation of a comprehensive observation system for biodiversity that can be used by natural resource planners, governments, scientists and researchers. Extensive data on biodiversity factors is not widely available in many developing countries, yet these nations are home to most of the world's unprotected biodiversity.

GEO-BENE research in South Africa revealed that poor quality data often led decision makers to overestimate the amount of land needed for conservation areas. Managing this extra land for conservation purposes costs a lot of money. Therefore, investing in the gathering of high quality data will help to make the establishment and management of conservation areas more cost effective and free up more land for other uses.

A secure food supply

In the area of agriculture, GEO-BENE's aim is to have a global land use and food distribution information service that can enable sustainable development through wise planning of land resources. For example, research so far has shown that the planned biofuels programmes of Europe, the US, Brazil, China and India may cost billions of euros more than anticipated.

Project results have also shown the benefits of using Global Earth Observation to identify geographic centres of malnutrition to efficiently plan aid operations. Other results from the project include the establishment of a database for global data modelling, the creation of an EPIC model (a system that can simulate agricultural ecosystem processes), an analyses of global nitrogen levels in cropland and a study of the impact of climate change on food production and agricultural water use around the world.

Energy and water: balancing supply and demand

Energy is vital to our day-to-day lives – in the food we cook, the work we do, our homes and our transport systems. It is also responsible for much of the world's current high pollution levels. GEO-BENE found that more certainty about climate sensitivity through the acquisition of better Global Earth Observation data will lead to better informed climate change and energy policies and more stable CO_2 prices. Under these conditions, energy producers' profits would be expected to rise, while CO_2 emissions are likely to fall.

Water conservation is becoming more and more important as a result of global warming and desertification in certain parts of the world. The EU needs clear water conservation and water resource management policies. GEO-BENE surveys have highlighted areas of emerging water scarcity and availability using remote sensing information. This technique increases the availability of water quality information such as early warnings of water shortages.

Limiting damage from disasters

The project is also studying a range of natural and man-made hazards such as forest fires and earthquakes to help develop better disaster management policies.

In the health field, GEO-BENE is investigating how Global Earth Observation information on factors such as climate and weather could help health systems detect disease epidemics early on. Global Earth Observation data could then be used to plan vaccination programmes, if necessary. Another GEO-BENE study is looking at whether the season and weather affect the risk of a patient dying from acute myocardial infarction.

Putting Global Earth Observation in the spotlight

GEO-BENE has had a high public impact with articles in journals such as Nature and Science. Working with the Group on Earth Observation (GEO), it has had a direct impact on government policies, such as the UK's Gallagher Review on Biofuels, and on World Bank strategies and financing. Special focus has also been put on policy processes under the United Nations Framework Convention on Climate Change (UNFCCC).

Thanks to GEO-BENE's work, the usefulness of Global Earth Observation benefit assessment is now widely recognised, paving the way for its application in diverse situations around the world.

Title | Global Earth Observation – Benefits Estimation: Now, Next and Emerging
Acronym | GEO-BENE
EC Contract number | 37063
Website | http://www.geo-bene.eu/

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• Swiss Federal Institute for Environmental Science and Technology EAWAG (Switzerland)
• University Freiburg FELIS (Germany)
• Vrije Universiteit Amsterdam IVM (Netherlands)
• National Public Health Institute KTL (Finland)
• Potsdam Institute for Climate Impact Research PIK (Germany)
• Soil Science and Conservation Research Institute SSCRI (Slovakia)
• University Bratislava UBR (Slovakia)
• University of Hamburg UHH (Germany)
• Council for Scientific and Industrial Research of South Africa CSIR (South Africa)
• National Institute for Environmental Studies NIES (Japan)

GLOBAL EARTH OBSERVATION SYSTEM OF SYSTEMS (GEOSS)

Steffen Fritz, Ian McCallum, Michael Williams, Florian Kraxner and Michael Obersteiner

Definition

Global Earth Observation System of Systems (GEOSS). GEOSS aims to involve all countries of the world to integrate ground-based (in-situ), airborne and space-based observation networks. Those Earth Observation (EO) systems which participate in GEOSS retain their existing mandates, but share primary observational data as well as information derived from those observations. The sharing of and access to data is enabled through common data standards. GEOSS is designed to address nine societal benefit areas namely ecosystems, biodiversity, health, disasters, energy, climate, weather, water and agriculture. GEOSS seeks to connect the producers of environmental data and decision-support tools with the end users of these products, with the aim of enhancing the relevance of Earth observations to global issues. The end result is a global public infrastructure that generates comprehensive, near-real-time environmental data, information and analyses for a wide range of users. The Group on Earth Observations (GEO www.earthobservations.org) is coordinating efforts to build GEOSS on the basis of a 10-Year Implementation Plan (GEO, 2005) running from 2005 to 2015. GEO is a voluntary partnership of governments and international organizations. GEO meets in Plenary at the senior official level and periodically at the ministerial level. Decisions are taken via consensus of GEO members.

Introduction

We are currently faced with major challenges due to the powerful processes which drive global change. These processes operate at a global scale and can only be observed, understood and predicted by a system that operates at a supranational level. These processes can have important consequences for human wellbeing and the monitoring of these processes is critical in order to understand the complex system of the earth's terrestrial and maritime biospheres.

It is envisaged that through GEOSS the information available to decision-makers at all levels will be improved, specifically relating to human health and safety, protection of the global environment, the reduction of losses from natural disasters, and achieving sustainable development. GEOSS is founded on the principle that better international co-operation in the collection, interpretation and sharing of EO information is an important and cost-effective mechanism for achieving this aim (Fritz et. al, 2008). GEOSS will yield a broad range of societal benefits, notably:

1. Reducing loss of life and property from natural and human-induced disasters;
2. Understanding environmental factors affecting human health and well-being;
3. Improving the management of energy resources;
4. Understanding, predicting, mitigating, and adapting to climate variability and change;
5. Improving water resource management via better understanding of the water cycle;
6. Improving weather information, forecasting and warning;
7. Improving management and protection of terrestrial, coastal and marine ecosystems;
8. Supporting sustainable agriculture and combating desertification; and
9. Understanding, monitoring and conserving biodiversity.

These correspond to the nine Societal Benefit Areas (SBAs) referred to as disaster, health, energy, climate, water, weather, ecosystems, agriculture and biodiversity.

Origin of GEOSS

As a result of the Earth Summit in Brazil in 1992, Agenda 21 identified the bridging of the gap between data collection and information required by decision makers as a key priority. As a result of the Summit three different observing systems were formed, namely the Global Climate Observing System (GCOS), the Global Ocean Observing System (GOOS), and the Global Terrestrial Observing System (GTOS). The 2002 World Summit on Sustainable Development in Johannesburg highlighted the urgent need for coordinated observations relating to the state of the Earth. It was realised that only by linking and co-ordinating the current observing systems could complex earth processes (in an increasingly environmentally stressed world) be understood (GEO, 2005). The First Earth Observation Summit convened in Washington, D.C., in July 2003, adopted a Declaration establishing the ad hoc intergovernmental Group on Earth Observations (ad hoc GEO) to draft a 10-Year Implementation Plan. The Second Earth Observation Summit in Tokyo, Japan, in April 2004 adopted a Framework Document defining the scope and intent of a Global Earth Observation System of Systems (GEOSS). The Third Earth Observation Summit, held in Brussels in February 2005, endorsed the GEOSS 10-Year Implementation Plan and established the intergovernmental Group on Earth Observations (GEO) to carry it out (Plag, 2006)

The Group on Earth Observation (GEO)

GEO is building GEOSS on the basis of a 10-Year Implementation Plan (GEO, 2005). The GEO Member Governments and Participating Organisations are supported by the GEO Secretariat based in Geneva, Switzerland. The Secretariat consists of a Director appointed by the Executive Committee, several international civil servants, and 8-10 national technical and scientific experts who are seconded to the Secretariat for two or three years. The Secretariat is responsible for coordinating the Tasks and other activities that are driving the 10-Year Implementation Plan for GEOSS. The secretariat also services the Plenary and the Committees and implements outreach and other support activities.

Earth Observation Systems

EO systems consist of instruments and models designed to measure, monitor and predict the physical, chemical and biological aspects of the Earth system. Buoys floating in the oceans monitor temperature and salinity; meteorological stations and balloons record air quality and rainwater trends; sonar and radar systems estimate fish and bird populations; seismic and Global Positioning System stations record movements in the Earth's crust and interior; some 60-plus high-tech environmental satellites scan the planet from space; powerful computerized models generate simulations and forecasts; and early warning systems issue alerts to vulnerable populations.

These various systems have typically operated in isolation from one another. In recent years, however, sophisticated new technologies for gathering vast quantities of near-real-time and high-resolution EO data have become operational. At the same time, improved forecasting models and decision-support tools are increasingly allowing decision makers and other users of EO to fully exploit this widening stream of information.

With investments in EO now reaching a critical mass, it has become possible to link diverse observing systems together to paint a full picture of the Earth's condition. Because the costs and logistics of expanding EO are daunting for any single nation, linking systems together through international cooperation also offers cost savings.

Implementing GEOSS

As a networked system, GEOSS is owned by all of the GEO Members and Participating Organizations. Partners maintain full control of the components and activities that they contribute to the system of systems. Implementation is being pursued through a Work Plan (GEO, 2008) currently consisting of over 70 tasks. Each task supports one of the nine SBAs or four transverse areas and is carried out by interested organisations.

GEO Work Plans are triennially revised and provide the agreed framework for implementing the GEOSS 10-Year Implementation Plan 2005-2015 (www.earthobservations.org/documents). These work plans consist of a set of practical tasks that are carried out by various GEO members and participating organizations. Connections will be realized between diverse observing, processing, data-assimilation, modeling, and information-dissemination systems. This will make it possible to obtain a considerably increased range of data sets, products and services on the key aspects of the Earth system. The plans are also focussing on enhancing the role of users and reflect the inputs and engagement of the communities of practice, taking full account of the Integrated Global Observing Strategy (IGOS, www.igospartners.org/) transition into GEO.

Governments and Participating organizations have advanced GEOSS by contributing a variety of "Early Achievements"; these "First 100 Steps to GEOSS" (http://www.earthobservations.org/documents/the_first_100_steps_to_geoss.pdf) were presented to the 2007 Cape Town Ministerial Summit.

World wide, several parallel initiatives are contributing their data to GEOSS. Inter alia, Europe is establishing Global Monitoring for Environment and Security (GMES www.gmes.info), the US is building the Integrated Earth Observation System (IOES http://usgeo.gov/), and China and Brazil are collaborating through the China-Brazil Earth Resources Satellite Programme (CBERS, www.cbers.inpe.br), which is launching a new Earth observation service that will provide state-of-the-art images of the planet to end-users throughout Africa free of charge.

The ultimate objective of GEOSS is to develop the use of EO by a broad range of user communities – from both developed and developing countries and ranging from decision- and policy-makers to scientists, industry, international governmental, and non-governmental organizations. Engagement of these communities to identify their needs for new or improved data is essential to enhancing the adequacy of provided services and products for a wide diversity of applications.

Data Standards and Data Dissemination

Due to the fact that EO data is obtained from a multitude of sources, an enormous effort is required among different governments and user groups to achieve true data interoperability (Durbha, et. al, 2008). Therefore, common standards for architecture and data sharing are essential. (see GEOSS best practices WIKI http://wiki.ieee-earth.org/ and the GEOSS Standards and Interoperability Registry www.earthobservations.org/gci_sr.shtml). Each contributor to GEOSS must subscribe to the GEO data-sharing principles, which aim to ensure the full and open exchange of data, metadata and products. These issues are fundamental to the successful operation of GEOSS.

The architecture of an Earth observation system refers to the way in which its components are designed so that they function as a whole. Each GEOSS component must be included in the GEOSS registry and configured so that it can communicate with the other participating systems. The GEOSS Components and Services Registry provides a formal listing and description of all the Earth observation systems, data sets, models and other services and tools that together constitute the Global Earth Observation System of Systems (www.earthobservations.org/gci_cr.shtml).

GEOSS will disseminate information and analyses directly to users. GEO is developing the GEOPortal (www.geoportal.org) as a single Internet gateway to the data produced by GEOSS. The purpose of GEOPortal is to make it easier to integrate diverse data sets, identify relevant data and portals of contributing systems, and access models and other decision-support tools. For users without good access to high-speed internet, GEO has established GEONETCast (http://www.earthobservations.org/geonetcast.shtml), a system of four communications satellites that transmit data to low-cost receiving stations maintained by the users.

Activities under the SBAs

1) SBA Disasters

GEOSS implementation will bring a more timely dissemination of information through better coordinated systems for monitoring, predicting, risk assessment, early warning, mitigating, and responding to hazards at local, national, regional, and global levels (GEO, 2005). Cozannet et al. (2008) describe a prototype catalogue that was developed to improve access to information about sensor networks surveying geological hazards (geohazards).

Related Project: e.g.: GFMC (www.fire.uni-freiburg.de/)

2) SBA Human Health

GEOSS will improve the flow of appropriate environmental data and health statistics to the health community, promoting a focus on prevention and contributing to continued improvements in human health worldwide (GEO, 2005).

Related Project: e.g.: PROMOTE (http://www.gse-promote.org/)

3) SBA Energy Resources

GEOSS outcomes in the energy area will support: environmentally responsible and equitable energy management; better matching of energy supply and demand; reduction of risks to energy infrastructure; more accurate inventories of greenhouse gases and pollutants; and a better understanding of renewable energy potential (GEO, 2005). Related Project: e.g.: ENVISOLAR (http://www.envisolar.com/)

4) SBA Climate

GEOSS outcomes will enhance the capacity to model, mitigate, and adapt to climate change and variability. Better understanding of the climate and its impacts on the Earth system, including its human and economic aspects, will contribute to improved climate prediction and facilitate sustainable development while avoiding dangerous perturbations to the climate system (GEO, 2005). A global climate observation system is essential to improve our understanding of the climate system and our ability to anticipate trends (Fellous, 2008).

Related Project: e.g.: APEC (http://www.apcc21.net/)

5) SBA Water

GEOSS implementation will improve integrated water-resource management by bringing together observations, prediction, and decision-support systems and by creating better linkages to climate and other data. In situ networks and the automation of data collection will be consolidated, and the capacity to collect and use hydrological observations will be built where it is lacking (GEO, 2005).
Related Project: e.g.: GRDC (http://grdc.bafg.de/servlet/is/Entry.987.Display/)

6) SBA Weather

GEOSS can help fill critical gaps in the observation of, for example, wind and humidity profiles, precipitation, and data collection over ocean areas; extend the use of dynamic sampling methods globally; improve the initialization of forecasts; and increase the capacity in developing countries to deliver essential observations and use forecast products. Access to weather data for the other SBAs will be facilitated (GEO, 2005).
Related Project: e.g.: TIGGE (http://tigge.ecmwf.int/)

7) SBA Ecosystems

GEOSS implementation will seek to ensure that methodologies and observations are available on a global basis to detect and predict changes in ecosystem condition and to define resource potentials and limits. Ecosystem observations will be better harmonized and shared, spatial and topical gaps will be filled, and in situ data will be better integrated with space-based observations. Continuity of observations for monitoring wild fisheries, the carbon and nitrogen cycles, canopy properties, ocean colour, and temperature will be set in place (GEO, 2005). This SBA is strongly linked to supporting the monitoring of the state of Forests and to provide essential information to the UNFCCC process for REDD activities as well as the monitoring of illegal logging.
Related Project: e.g.: POSTEL (http://postel.mediasfrance.org)

8) SBA Agriculture

GEOSS implementation will address the continuity of critical data, such as high-resolution observation data from satellites. A truly global mapping and information service, integrating spatially explicit socio-economic data with agricultural, forest, and aquaculture data will be feasible, with applications in poverty and food monitoring, international planning, and sustainable development (GEO, 2005).
Related Project: e.g.: GAMS (http://www.earthobservations.org/cop_ag_gams.shtml)

9) SBA Biodiversity

Implementing GEOSS will unify many disparate biodiversity-observing systems and create a platform to integrate biodiversity data with other types of information. Taxonomic and spatial gaps will be filled, and the pace of information collection and dissemination will be increased (GEO, 2005). Since biodiversity data in general is not lacking, but often uneven in its spatial, temporal and topological coverage as well as physically dispersed and unorganised, the GEOBON project tries to overcome these shortcomings by installing a system which aims to organize the information, increase the exchange between suppliers and users, and to create a mechanism whereby data of different kinds, from many sources, can be combined (Scholes et al, 2008).
Related Project: e.g.: GEOBON www.earthobservations.org/cop_bi_geobon.shtml

Conclusions

Without a global effort to link all current observing systems to build the Global Earth Observation System of Systems (GEOSS), modern civilisation will be struggling to understand the complex chemical, biological and physical processes of the Earth system. Therefore, GEOSS is needed more than ever to acquire comprehensive, near-real time environmental data, information and analysis by users as well as decision makers to respond more effectively to the plethora of environmental challenges.

Since the establishment of the Group on Earth Observations (GEO), many early achievements have been realised. These are documented in www.earthobservations.org under each of the nine GEOSS themes or Societal Benefit Areas (SBAs). However, the active mobilisation of data users and providers will remain necessary to make GEOSS a success (Fellous, 2008).

Many EO resources have been created, and are available to the global community, in order to support scientists, decision makers, and the general populace. To realize a successful GEOSS, the key is to provide mechanisms that enable EO data and geospatial data from those resources to be processed, shared and coordinated (Hassan & Huh, 2008). To this end, the GEOPortal (www.geoportal.org) has been developed as the Internet gateway to the data produced by GEOSS.

Global Earth Observations (EO) may be instrumental to achieve sustainable development, but to date there have been no integrated assessments of their economic, social and environmental benefits. The project, Global Earth Observation – Benefit Estimation (GeoBene www.geo-bene.eu) is developing methodologies and analytical tools to assess the societal benefits of GEOSS. First results from the Geo-Bene project illustrate that the overall societal benefit is by far higher than the incremental costs necessary to establish GEOSS.

Bibliography

Cozannet, G.L., Hosford, S., Douglas, J., Serrano, J.J., Coraboeuf, D., Comte, J., 2008. Connecting Hazard Analysts and Risk Managers to Sensor Information. Sensors, 8:3932-3937

Durbha, S.S., King, R.L., Younan, N.H., 2008. An information Semantics Approach for Knowledge Management and Interoperability for the Global Earth Observation Systems of Systems. IEEE Systems Journal (in press)

Fellous, J.L., 2008. Towards a global climate observing system. Interdisciplinary Science Reviews, 3:83-94

Fritz, S, Scholes, R, J., Obersteiner, M., Bouma, J., Reyers, B., 2008. A Conceptual Framework for Assessing the Benefits of a Global Earth Observation System of Systems. IEEE Systems Journal (in press)

GEO, 2005. Global earth observation system of systems: 10-year implementation plan reference document. ESA, 209 pp (www.earthobservations.org/documents)

GEO, 2008. GEO 2007-2009 Work plan toward convergence. GEO, 30 pp. (www.earthobservations.org/documents/wp0709_v6.pdf)

Plag, H.P., 2006. Geo, Geoss and Igos-P: The framework of Global Earth Observations.

(http://nng.esoc.esa.de/ws2006/Papers/01_Plag_geo_pospaper_11pt_new.pdf.gz)

Scholes, R.J., Mace, J.M., Turner, W., Geller, G.N., Jürgens, N., Larigauderie, A., Muchoney, D, Walther, B.A., Mooney, H. A., 2008. Towards a Global Biodiversity Observing System. Science, 321:1044 - 1045

Cross-references

Global Climate Observing System (www.wmo.int/pages/prog/gcos)
Global Land Observing System (available at: http://usgeo.gov)
Global Oceans Observing System (www.ioc-goos.org)
Cryosphere and Polar Region Observing System (available at: www.igospartners.org)

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A real options approach to satellite mission planning

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Abstract

Satellite missions are one instrument of Earth observation targeted at obtaining information for improved decision making in sustainable development. But satellite missions are expensive undertakings involving large sunk costs and facing uncertain benefit streams. In the area of avoiding damages through, for example, better weather forecasts or better-informed rescue missions, the benefits are high, but also difficult to quantify. Using real options to optimize the timing of the launch of a satellite enables us not only to optimize the timing of the mission, but also to derive the value that such information conveys when it can be used to reduce the extent of the damage from disasters and their consequences: with low benefit expectations or large uncertainty, launching will be postponed, so ex ante Earth observation benefit assessment is an important task.

1. Introduction

Recent political efforts such as the Group on Earth Observations (GEO),[1] in which 72 governments and the European Commission participate, acknowledge and emphasize the need to make better scientific information available. This implies that more comprehensive and timely data about the planet's physical, chemical and biological systems should be collected.[2] One means for such data gathering is through satellite missions. However, satellite missions are costly and public officials might be reluctant to commit resources to the launch of another satellite if the ensuing benefit streams are not certain ex ante. In economic terms, once the satellite mission has been started, all resources committed are largely sunk and the situation is, thus, characterized by irreversible investment. On the other hand, future benefits are potentially very high if we think of the environmental and economic damage that could be avoided or at least better forecast and alleviated if unavoidable. Better weather forecasts, for example, could lead to improvements in early warning systems in case of disasters, and thus to great reductions in economic losses as well as in losses of human life. Yet such benefits are difficult to estimate and quantify ex ante and this reduces the incentive for satellite launches—both from the point of view of private investors and of government budgets.

What we are essentially facing is an investment problem in terms of launching a new satellite under uncertainty about future benefit streams[3] in a context of irreversibility associated with the large sunk costs connected to satellite missions. Such problems can be addressed in a real options framework [2], which takes into account investment irreversibility, uncertainty and the flexibility to time the satellite launch differently as new information arrives. We adopt such a framework here, and apply it to a satellite mission considered to bring about new scientific information potentially leading to lower damage from disasters. However, these benefits will be very volatile and difficult to predict: if there is no disaster, then the benefits are low,

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[1]See http://www.earthobservations.org.

[2]In addition, Harris and Browning [1] point to the need for coherency in existing databases and information sources, since differences in legal protection, data formats, metadata, distribution, pricing and archiving make the information that already exists difficult to use.

[3]It is important to emphasize at this point that modelling the timing of a satellite launch as a function of these benefit streams is a simplification, which abstracts from other factors influencing the launching decision in practice. Such factors include the extent to which the development phase is successful, for example, because unforeseen technical problems and organizational shortcomings can lead to delays. Another example is uncertainty about political issues that might arise, e.g. in connection with the place of launch and other associated decisions.

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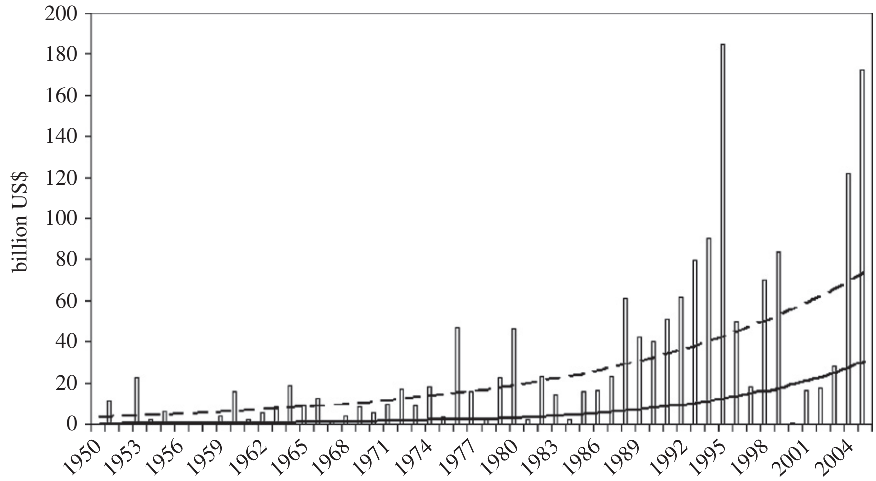

Fig. 1. *Economic losses from disaster incidents*. The bars show the total economic losses from disasters in 2005 US$ billion. The dashed line is the trend in uninsured, the solid line the trend in insured losses. Source: OECD Information Technology Outlook 2006 [3].

but if the new information helps to preserve people and equipment from such a disaster, the benefits can be immense.

Disasters can be of a climatic nature, involving floods, wild fires or extreme temperature episodes, or they may be lithosphere disasters, including earthquakes and landslides. Finally, epidemics can be related to the previous two categories, but have a dynamic impact structure as well. Fig. 1 shows that there has been a clear upward trend in the economic losses from disasters over the past few decades, which might be associated with the increased rate of global warming leading to more extreme weather situations, more intense storms, the melting of icecaps, glaciers and permafrost, etc.[4]

The development of the losses in Fig. 1 can be considered as a stochastic process, where the spikes can be interpreted as the occurrences of high-impact disasters on top of those disasters, which lead to an increasing average amount of losses denoted by the trend line. The value of additional information from a satellite mission for disaster mitigation is then represented by the ability to reduce this average amount of losses. Note that, in contrast to models where the value of information is derived by comparing the decisions taken in the face of stochastic processes to those taken in a deterministic setting, the framework in this paper follows a different approach, since we do not think that the occurrence of high-impact disasters can be avoided most of the time. However, better warning systems and also damage mitigation through improved and better informed rescue operations *after* the event of a disaster can significantly reduce the average losses depicted in Fig. 1.

In the following, we will first present an overview of the literature on expected value of information and show how our approach differs from this. Then the model is outlined and solved. This can be done analytically for the simple case considered, but it is also possible to extend the model, for example to include more than one stochastic benefit stream.[5] Such extensions complicate the computations, but it is no problem to solve the model numerically with stochastic backward dynamic programming methods. We will include two extensions that can be solved in the analytical framework and present the numerical results for another extension with two stochastic benefit streams, before concluding with a summary and some ideas for further research.

2. The value of information—existing literature and applications

As pointed out by Macauley [4], most information models find that the value of information largely depends on four important factors: (1) the extent of uncertainty on the part of decision makers; (2) the cost of making a decision, which is not optimal in the light of better information; (3) the cost of making use of the information and incorporating it into decisions; and (4) the price of the next-best substitute for the information. In other words, the value of information can be interpreted as the willingness to pay of the decision makers concerned.

With a simple example Macauley shows that the value of information is zero when the decision maker attaches a probability of zero or one to the events that are thus no longer uncertain in his or her view [4]. The other cases (where information has no value) occur when there are no alternative actions available, even if information can be

[4]Another factor is the increase in the amount of physical wealth, materials and equipment that can be damaged as economies expand. In this way, there is just *more* that can be damaged.

[5]Private investors can include research equipment on their satellites that are otherwise used to deliver communication and location services, for instance, to receive payments from agencies or institutes that then use the collected data. This is generally known as "hosted payload" and can make the launch of a satellite more attractive when it is probable that additional income can be secured. We show a simple case considering a hosted payload, which can be solved analytically.

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obtained, or when a wrong decision will not result in any costs. In the same vein information is most valuable when the costs associated with a wrong action are high, when many alternative actions are available and when the decision maker has no extreme preference for one or more of the alternatives.

She then goes on to categorize the methods by which the expected value of information has previously been measured into two subsets. First, studies that use wage and/or housing prices to infer the value of, say, weather information because the latter can be expected to be capitalized in these prices and so it makes sense to deduce the value from existing time series; this is what Macauley calls "hedonic pricing studies" [4]. The second subset includes all studies that measure the value of information by gains in output or productivity, even though the value of information is generally found to be rather small in most of the studies. Macauley attributes this to the fact that people are obviously only willing to pay for information ex ante and are often not aware of the severe consequences that the lack of information in the case of an uncertain event can have. Similarly people often only attribute a very low probability to catastrophic events and then choose not to pay for information that might itself be rather costly.

In the end, she deems the computation of expected values of information a very suitable tool for the valuation of Earth observation benefits, where the availability of information can save costs, lives and alleviate misery in the face of disasters. In economics—and more specifically in the area of climate change policies—the expected value of information has been a well-known tool for years. Peck and Teisberg [5] and Nordhaus and Popp [6] are examples adopting a cost–benefit approach to finding the optimal policy response to climate change damage and to estimating how much the world would be better off economically, if climate sensitivity and the level of economic damage were known. In general, these studies use multi-stage optimization where all information about the correct level of the uncertain parameters arrives in one time instance. Others, like Fuss et al. use stochastic dynamic programming, allowing for a rich description of the evolution of the uncertain parameters but with the disadvantage of having less scope in terms of controls and states [7]. They derive the value of information by comparing profits and emissions when optimizing with stochastic prices to the case where prices are deterministic (and therefore the optimal decisions are different).

Another area is the estimation of the abovementioned merits of early warning systems. Lave and Apt employ a stochastic cost–benefit framework to the valuation of control structures (e.g. dams and levees), of mitigation policies (e.g. construction standards in the face of natural disasters), and of the benefits of information for early warning and evacuation in the USA [8]. Especially for the latter they find large scope for improvement through better information. In addition, the availability of information ex ante should lead people to make better decisions about matters like the areas that they choose to live in. The authors emphasize that economically much could be saved by informing people that they will have to bear the consequences when they move to high-risk areas because the lack of opportunity for moral hazard will lead them to refrain from decisions they would have made when they expected government and insurance to alleviate their losses.

A similar conclusion is found by Khabarov et al., who conduct simulation studies to estimate the benefits of a finer grid of weather stations and more frequent patrols in forest areas, so that wild fires can be detected earlier and—if not prevented—at least limited or extinguished before they can spread to a larger area, and thus cause economic damage and endanger the life of humans and animals [9]. They find that the addition of more weather stations does indeed reduce the fraction of the area burnt by wild fires.

Other studies show that not only are the ex ante prophylactic actions facilitated by better observation information, but also the losses that can be expected after a catastrophe has struck may be significantly reduced if rescue teams can be better informed and coordinated. Let us consider the example of an earthquake: while there is definitely no possibility of stopping an earthquake occurring in the first place, and the scope for early warning systems is limited by the lack of understanding of the deep underground geophysical processes involved, it is important to note that a high percentage of the deaths caused in an earthquake actually occur after the event, because long response times jeopardize the success of rescue operations. These response times could be significantly shortened by obtaining better information that can then serve to accelerate the assignment of rescue brigades to specifically damaged areas. Moltchanova et al. use a stochastic framework to model the dependence of an earthquake rapid response system (in a virtual city of standard size) on available information and resources [10]. They find that, for any level of available (rescue) resources, the efficiency of saving lives is higher when those involved are better informed and can thus coordinate operations much more effectively.

In Macauley's terms [4], our work falls into her second subset because we assume that, through better information provided by Earth observation, a portion of the damage can be mitigated, which can also be interpreted as a gain in economic output that would otherwise have been lost. The framework used in this paper is different from those developed by Nordhaus and Popp [6] and others, where multi-stage optimization is employed and the gains from having information that arrives in a certain time period are measured. In contrast, we develop a real options model where the uncertainty about the occurrence of disasters and their economic impact persist throughout the planning period. The approach is also different from Fuss et al.'s real options model mentioned above [7], since the latter derives the value of information by comparing decisions and the resulting profits (and emissions) under uncertainty with those derived under certainty, while here the spikes in

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the stochastic process of economic losses cannot be removed by the availability of better information: the level of economic losses can only be dampened through mitigation and prevention but the event of the disaster itself cannot be avoided.

3. A real options framework for optimal timing of a satellite launch

The decision maker in a satellite mission planning procedure does not necessarily have to be a private person or entity. Most probably it will be government officials or agencies deciding about the allocation of the budget to such a project, especially where the collection of policy-relevant data is concerned. In this model, we just consider the costs and benefits of the satellite mission over time and neglect the problem of raising funds for the mission. Instead, we assume that potential benefits net of the costs incurred to obtain these benefits should be maximized. This will be referred to as "net benefits".

The model determines the optimal timing of the satellite mission for a single decision maker. The latter faces an uncertain net benefit stream in terms of reduced economic losses, but these are hard to estimate ex ante. In addition, such a mission is very costly and most of these costs will be sunk as well. The planner can exercise the option to launch immediately or wait until s/he learns more about the development of the net benefits, i.e. the economic losses that can be avoided. On the other hand, waiting also implies that these benefits cannot be enjoyed in the meantime, yet these might be very high in terms of avoided economic, environmental and even human losses.

The planner's decision problem is to maximize expected net benefits under uncertainty. Let us denote the benefits by B,

$$B_t = \theta L_t \tag{1}$$

where L_t represents the economic losses, which correspond to the height of the bars in Fig. 1 in Section 1. θ is the fraction of L that can be saved thanks to improved information from Earth observation and is constant over time, as damage can never be reduced beyond a certain minimum impact. As an example consider the loss reduction in the case of better-informed rescue missions after an earthquake: even though more people might be saved, most buildings will be irreversibly damaged, as will large parts of the infrastructure. In other words, the risks involved in the occurrence of natural disasters might not be completely avoidable, but the vulnerability represented by low values of θ can be decreased by obtaining better information through Earth observation.

Furthermore, since disasters strike sporadically and not continuously over time, the loss needs to be modelled as a stochastic process. Since the losses depicted in Fig. 1 additionally have a positive trend, we assume that they follow a geometric Brownian motion (GBM):

$$\mathrm{d}L_t = \mu L_t \mathrm{d}t + \sigma L_t \mathrm{d}z_t \tag{2}$$

where μ is the trend, σ the volatility parameter and $\mathrm{d}z_t$ the increment of a standard Wiener process. Referring back to Eq. (1), since the benefit is just a fraction θ of the losses L, B also follows a GBM with the same parameters.

The costs of a satellite mission can be divided into two parts: first, there will be costs for developing and launching the satellite. Later on, there will be costs of operating and maintaining ($O\&M$) it, where the latter are typically much lower than the development and launching ($D\&L$) costs. The net benefits from earth observation are represented by the difference between B_t and these costs,

$$NB_t = B_t - O\&M = \theta L_t - O\&M \tag{3}$$

In real options theory (see [2]), the decision maker holds an investment option and, as long as the option value (of holding on to it) is larger than the value that would be received upon exercising the option, investment does not occur. There is thus a threshold value in the face of uncertain processes and large up-front sunk costs that needs to be reached in order to trigger investment. Applied to the problem at hand, there will be a level of expected mitigated losses that will trigger the launch of the satellite. The value of the satellite mission at the time if launching if the satellite is launched at time t—or the immediate value of (Earth observation) information from 0 to T—is

$$V(B_t) = E\left[\int_0^T \mathrm{e}^{-rt}(B_t - O\&M)\mathrm{d}t\right] \tag{4}$$

where T is the lifetime of the satellite—which will be assumed equal to ∞ for the moment—and r is the discount rate. Integration delivers

$$V(B_t) = \frac{B_t}{r-\mu} - \frac{O\&M}{r} \tag{5}$$

This is the value of the Earth observation benefits if the satellite is launched immediately, which happens only when $V(B_t)$ surpasses the value of the launching *option* or in other words the value of waiting and acting optimally later. The latter will be denoted by $F(B_t)$. In order to determine the point in time when this happens, we have to find the critical level of mitigated losses, B^* that will trigger the launch.

Following the procedure presented in Dixit and Pindyck [2], the following differential equation holds for $B \in [0, B^*]$, where we omit time subscripts for ease of exposition:

$$rF(B) = \mu BF'(B) + \frac{\sigma^2}{2}B^2F''(B) \tag{6}$$

Eq. (6) is the result of some transformations and the application of Itô's Lemma and basically equates the marginal value of waiting (and earning interest on the unspent money in the meantime) with the value of exercising the option to launch that evolves according to the changes in $F(B)$ over time. Together with the boundary conditions, it can then be used to derive the critical value of B^*.

The first boundary condition states that the option value should be zero as B tends to zero: if nothing can be saved or mitigated, then the investment option is not worth anything.

$$\lim_{B\to 0} F(B) = 0 \tag{7}$$

The other two conditions are called the "value-matching" and the "smooth pasting" conditions (see [2]), such that—at the critical value of B, B^*—the option value and the immediate value of launching (i.e. the net benefits) must be equal; and that there can be no kinks leading to contradictory results around the critical value.

$$F(B^*) = V(B^*) - D\&L = \frac{B^*}{r-\mu} - \frac{O\&M}{r} - D\&L = \frac{B^*}{r-\mu} - C \tag{8}$$

$$F'(B^*) = \frac{1}{r-\mu} \tag{9}$$

where C in Eq. (8) comprises all cost items, i.e. the term $((O\&M)/\mathrm{r}) - D\&L$ is replaced by C. Since this is analogous to the problem presented in Dixit and Pindyck [2], we can find the solution in the same way. The solution for the option value $F(B)$ has the form

$$F(B) = K_1 B^{\beta_1} + K_2 B^{\beta_2} \tag{10}$$

where $\beta_{1,2} = ((\sigma^2/2) - \mu \pm \sqrt{(\mu - (\sigma^2/2))^2 + 2r\sigma^2})/\sigma^2$. Since $\beta_2 < 0$, we are only interested in β_1. $K_2 = 0$ and $K_1 = (B^*)^{1-\beta_1}/\beta_1(r-\mu)$, which leads to the final solution for the critical threshold value, beyond which the satellite option is exercised,

$$B^* = \frac{\beta_1}{\beta_1 - 1}(r-\mu)C \tag{11}$$

$$L^* = \frac{\beta_1}{\beta_1 - 1}(r-\mu)C/\theta. \tag{12}$$

This already shows that high expectations about how much damage can be avoided or mitigated (i.e. the magnitude of the vulnerability parameter θ) will lead to an earlier timing of the satellite mission: the larger θ, the lower will be the level of losses, and thus also potential benefits that will trigger the launch of the Earth observation satellite.

Using data and estimates from a PricewaterhouseCoopers report on the Galileo Programme[6] (prepared at the request of the European Community) [11], we can then verify at which level of losses (or more precisely benefits in terms of mitigated damages, B^*) the satellite launch will optimally occur. Since the study assumes that there is also a relatively certain amount of commercial income from selling communications and location services, the term C in Eq. (11) changes to $C = ((-\pi + O\&M)/r) + D\&L$, where π is the (deterministic) income from commercial uses of satellite services.

The study estimates that €3.406 billion will be needed for $D\&L$. For the revenues the estimates vary considerable with respect to the underlying assumptions (between €300 and €600 million).[7] $O\&M$ cost estimations amount to €220 million.

In addition, the OECD *Information Technology Outlook 2006* estimates the trend of the economic losses (see Fig. 1) to be 5.145%. σ is at 10%, even though it can be seen from Eq. (11) and the composition of β that a larger volatility parameter will lead to an increase in the option value and therefore a larger threshold value, B^* or L^*. In other words, the satellite will be launched only when a higher level of damages has been reached.

With these estimates B^* is equal to €173.351 million. Note that, while we think it defensible to deduce a general trend from the losses presented in Fig. 1, it is not admissible to compare the results from our theoretical exercise with the levels of the losses shown there. In fact, Fig. 1 is about the losses in the whole of the OECD and the satellite system analyzed would probably only be capable of saving a tiny fraction of those losses. In other words, θ would be very small.[8]

Nevertheless, we can derive some important conclusions from this analytical solution by conducting some sensitivity experiments. Fig. 2 displays the option value (dashed line) and the net present value (solid line) of the satellite mission. In the beginning, the option value exceeds the immediate value of launching, so it is worth waiting. The critical value triggering the launch of the Earth observation mission occurs at the intersection of the two lines. Increasing the volatility parameter will shift the option value line upwards, so that this point of intersection moves to a higher level of B. For $\sigma = 0.2$, for example, B^* becomes 214.69. In other words, an increase in the volatility of losses (and the associated value of earth observation) leads to a postponement of launching, as previously concluded from Eq. (11) and the composition of β. An increase in the trend shifts both lines upwards and makes them a bit steeper, so that the launch will occur somewhat earlier.

4. Extensions

4.1. Economies of scale

Instead of launching a satellite or a satellite system for the sake of collecting and using Earth observation data, governments can also take another route: it is not unusual that companies offer so-called "hosted payloads" to

[6]The Galileo System is of course not just based on a single satellite. In fact, it comprises 30 Medium Earth Orbit satellites and a "ground segment to control the satellites, distribute information and provide service centers for interface with users." (page 6 [11]).

[7]The study takes into account revenues from personal communications and location applications, commercial aviation, oil and gas rig positioning and land and transition zone seismic exploration and other sources.

[8]In addition, the graph is in 2005 US dollars, while the numbers used in our calculations are in 2001 euros.

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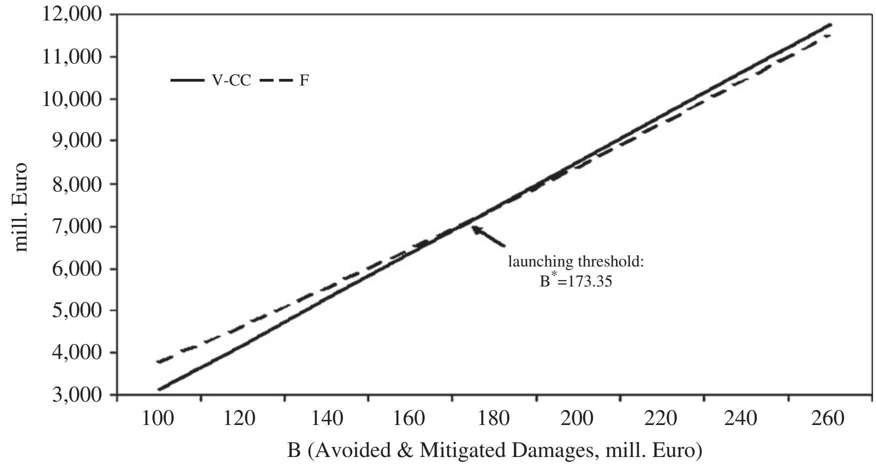

Fig. 2. Net present value (solid line) of launching satellite mission vs. option value (dashed line).

governments on their commercial satellites. The clear advantages of this are that cost risks can be distributed and the unit cost of these additional services are typically lower than in the case where two independent projects are launched for each purpose separately. In other words, adding hosted payloads can rightly be expected to benefit from economies of scale.

Similarly, governments could expand their own satellites by hosting more equipment, which could further improve the quality and amount of observations, while reducing the unit costs. So their vulnerability could be decreased (i.e. θ could be increased) without incurring the full cost of another satellite launch. In order to investigate this issue more closely, let us consider the profitability of two possible projects: (1) the launch of a satellite for earth observation purposes; and (2) the launch of the satellite combined with a hosted payload.

We assume the lifetime of both the satellite and the hosted payload to be infinite for now. We denote project i's capital costs as CC_i, and its operation and maintenance costs as OM_i. (This means that the capital costs of the hosted payload are CC_2-CC_1 and the operations and maintenance costs are OM_2-OM_1). The damages that can be avoided by having the project launched are considered to be θ_i, where $\theta_2>\theta_1$. We also assume $CC_1<CC_2$.

The aim of this exercise is to prove that the optimal decision is to invest in the second project, which will in turn lead to an earlier launch of the satellite, if the costs associated with the project follow economies of scale.

Using the notation introduced earlier, we will prove the following: assuming $(CC_1+(OM_1/r))/\theta_1>(CC_2+(OM_2/r))/\theta_2$, the optimal decision is to invest in the second project, where the optimal time of investment is sooner than in the case of the first project.

This assumption has a very straightforward explanation: $CC_i+(OM_i/r)$ are the costs associated with project i for its whole lifetime. This means that $(CC_i+(OM_i/r))/\theta_i$ represents the costs per unit of benefit achieved. Thus, if we assume economies of scale, we assume that having the satellite combined with hosted payload leads to a decrease in costs needed per unit of profit.

First, we look at a situation where we need to determine the optimal timing of investment into project i. As shown previously, the value of the option is the solution of the differential equation:

$$rF_i = \mu B F'_i + \frac{\sigma^2}{2} B^2 F''_i$$

for $B<B^*_i$ where $F_i(B^*_i)=V_i(B^*_i)-CC_i$, $F'_i(B^*_i)=V'_i(B^*_i)$. The general solution of the differential equation is $F_i(B)=K_{1,i}B^{\beta 1}+K_{2,i}B^{\beta 2}$, where $\beta_{1,2}=((\sigma^2/2)-\mu\pm\sqrt{(\mu-(\sigma^2/2))^2+2r\sigma^2})/\sigma^2$. It can be shown, that $\beta_1>1$ and $\beta_2<0$. Together with the condition $\lim_{B\to 0}F_i(B)=0$, we get $K_{2,i}=0$. $K_{1,i}$ and B^*_i can be derived from the value matching and smooth pasting conditions as

$$B^*_i = \frac{\beta_1}{\beta_1-1} C_i(r-\mu)$$

$$K_{1,i} = \frac{B_i^{*1-\beta 1}}{\beta_1(r-\mu)}$$

where $C_i=CC_i+OM_i/r$. And since we assume $(CC_1/\theta_1)>(CC_2/\theta_2)$, then

$$L^*_1 = \frac{B^*_1}{\theta_1} > \frac{B^*_2}{\theta_2} = L^*_2$$

From this, we can already observe that the optimal timing for project one (when L crosses the threshold L^*_1) is sooner than for project two (when L reaches L^*_2). The option value of the project i at any current state $L\leqslant(B^*_i/\theta_i)$ is

$$F_i(\theta_i L) = K_{1,i}(\theta_i L)^{\beta_1} = \frac{B^*_i}{(\beta_1-1)(r-\mu)}\left(\frac{\theta_i L}{B^*_i}\right)^{\beta_1}$$
$$= \frac{C_i}{(\beta_1-1)}\left(\frac{(\beta_1-1)\theta_i L}{\beta_1(r-\mu)C_i}\right)^{\beta_1}$$

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This means

$$\frac{F_1(\theta_1 L)}{F_2(\theta_2 L)} = \frac{C_1}{C_2}\left(\frac{C_2/\theta_2}{C_1/\theta_1}\right)^{\beta_1}$$

And since $C_1 < C_2$ and $(C_2/\theta_2) < (C_1/\theta_1)$ then $(F_1(\theta_1 L)/F_2(\theta_2 L)) < 1$. This implies that the value of the option to launch the first project is always less then the value of the option to launch the second one. In other words, the satellite with a hosted payload is not only the more attractive opportunity in terms of costs, but it is also launched earlier, which leads to a longer period of damage mitigation. In other words, hosted payload offers a win-win situation—both in terms of lower per unit costs and in terms of damage avoided.

4.2. Analytical solution with finite satellite lifetime

It is obvious that the assumption of an infinite satellite lifetime made in Section 3 does not hold in reality. Therefore, we want to relax this assumption here and investigate how the results change, if we take into account that the lifetime of a satellite is not infinite. In this case the integration in Eq. (4) delivers

$$V(B_t) = \frac{B}{r-\mu}(1 - e^{(\mu-r)T}) + \frac{\pi - O\&M}{r}(1 - e^{-rT})$$

Following the same procedure as in the previous section, we arrive at the following equation for the critical value of B:

$$B^* = \frac{\beta}{\beta - 1} C(r-\mu)\frac{1}{1 - e^{(\mu-r)T}}$$

where C is defined as before, and thus composed of the deterministic revenues from selling communications and location service and the costs of launching and maintaining the system. Note from the last equation that B^* is the same as in the case of infinite satellite lifetime multiplied by the term $1/(1-e^{(\mu-r)T})$. As T approaches infinity, the term will tend to 1 and therefore we will end up with the same B^* as in Eq. (11). In addition, the lower the expected lifetime of the equipment, the larger will this term be and therefore the mission will be postponed beyond the point in time that would have been optimal with an infinite lifetime. This makes intuitive sense, of course, since the mission will only provide benefits for a relatively short period of time in the case of a short lifetime of the equipment.

Adding the concept of economies of scale introduced in Section 4.1, we find our previous conclusions confirmed: following the same steps as for infinite lifetime of the satellite toward the solution of the differential equation for the option value, F, with the value-matching and smooth-pasting conditions for a satellite with the lifetime T we obtain

$$B_i^* = \frac{\beta_1}{\beta_1 - 1} C(r-\mu)\frac{1}{1 - e^{(\mu-r)T}}$$

$$K_i = \frac{C_i}{\beta_1 - 1}(B_i^*)^{-\beta_1}$$

And so the timing of the satellite without a hosted payload would occur later than with it

$$L_1^* = \left(\frac{(r-\mu)}{1 - e^{(\mu-r)T}}\right)\left(\frac{\beta_1}{\beta_1 - 1}\right)\frac{C_2}{\theta_2} = L_2^*$$

.

For the values of the options to invest into the projects 1 and 2 we get

$$F_i(\theta_i L) = K_i B^{\beta_1} = \frac{C_i}{\beta_1 - 1}\left(\frac{\theta_i L}{B_i^*}\right)^{\beta_1}$$

for $L < (B^*{}_i/\theta_i)$, and so

$$\frac{F_1(\theta_1 L)}{F_2(\theta_2 L)} = \frac{C_1}{C_2}\left(\frac{C_2/\theta_2}{C_1/\theta_1}\right)^{\beta_1} < 1$$

We can thus conclude that not only would the hosted payload initiate an earlier launch, but it would also increase the value of the investment, which means the investor would always prefer the second project.

4.3. A numerical application with two stochastic benefit streams

For reasons of comparison, we first use the numerical model with a deterministic income stream and a stochastic one, as in the previous subsection. The data are the same as in Section 3, except for the fact that we use a typical lifetime of 15 years for the satellite system.[9] B^* now amounts to €820.669 million, which is obviously substantially higher than in the infinite lifetime case.

Let us now extend the model to include not only stochastically growing benefits from Earth observation information in the form of mitigated or avoided damage, but also stochastic benefits from services sold commercially, as previously mentioned. We assume that the market will eventually reach an equilibrium and that the revenues from selling these services will, therefore, be mean-reverting.

$$d\pi_t = \alpha(\mu^\pi - \ln \pi_t)\pi_t dt + \sigma^\pi \pi_t dz_t^\pi$$

where π will revert to its long-term level e^{μ^π} at a speed of α. $dz_t{}^\pi$ is the increment of a standard Wiener process and σ^π is the corresponding volatility parameter.

The value function is then composed of benefits immediately received upon launching and the so-called "continuation value" contingent upon all possible future states and benefit and revenue realizations

$$V_t(x_t, B_t, \pi_t) = \max_{a_t(x_t)}\{\psi(x_t, a_t, B_t, \pi_t) + e^{-r}E(V_{t+1}(x_{t+1}, B_{t+1}, \pi_{t+1})|B_t, \pi_t)\}$$

[9] For a lifetime of 200 years or longer, we get the same result for B^* as before—with the analytical approach and infinite lifetime.

where x_t is the state (i.e. whether the satellite has been launched or not), which is determined by the action taken, a_t. $\psi(\cdot)$ is the immediate net benefit including both the revenues from selling services commercially and the benefits from avoiding or mitigating damage. This can be optimized to find the optimal timing of the launch by using backward dynamic programming.[10]

We set α equal to 0.5 and σ equal to 5% and find that B^* is 820.815 million €, which is not significantly different from B^* with deterministic π. In other words, the uncertainty conveyed by the fluctuations in the market price of communication and location services, for instance, does not seem to have a decisive impact on the critical value of the avoided damage stream triggering the satellite launch.[11]

It is important to note that these results are, of course, sensitive to the underlying parameter values. Sensitivity analysis shows that substantially lower levels for B (e.g. because of a higher than expected vulnerability to disasters, modelled through a lower than expected θ) or π combined with a large volatility of B can even lead to the result that the mission is not launched at all in many cases.[12]

5. Summary and implications

This paper has investigated the applicability of basic real options theory to the timing of a satellite mission in the context of the benefits that can be obtained from Earth observation and the ensuing improvement in the amounts and quality of data that can help to avoid or at least mitigate the damage from disasters. The analysis has shown that even a very simple framework in the style of Dixit and Pindyck [2] can be used to examine issues of uncertainty and optimal timing of launching the satellite (or the satellite system).[13] There are several important conclusions to be drawn from this.

First, large volatility of the benefits from damage avoided or mitigated increases the option value, and therefore leads to a postponement of the satellite mission. While it is completely rational to postpone and wait in the face of larger uncertainty, a higher σ also implies bigger spikes, representing high-impact disasters in our interpretation. This means that it is important to evaluate and assess the economic and social benefits that could be obtained through Earth observation. The same is true for the trend parameter: a larger value of μ has been shown to trigger an earlier launch. So, if ex ante benefit assessment can establish that μ can be expected to be relatively high, an Earth observation system could be installed earlier as well.

In addition, it is fair to assume that governments can expand their equipment on satellite missions at diminishing unit costs and, therefore, benefit from economies of scale. Application of the same analytical framework to this problem has shown that this would not only lead to potential increases in θ, and thus an increase in damage avoided damage (or lower vulnerability) at lower unit costs, but also to an earlier launch of the satellite and thus a prolonged period during which damage can be avoided or mitigated.

Furthermore, the shorter the lifetime of the satellite system, the longer will the option value exceed the net present value, and waiting will be worthwhile. By finding ways to refurbish satellites at relatively low cost or maintain them longer or make them more durable in the first place, this problem could be overcome.

Even though the numerical model in the last subsection did not find a significant impact of the volatility of the "commercial" benefit stream on the timing of the satellite mission, the results will most probably look very different when different price processes are tested for. As can be imagined, communications services, for example, can be subject to substantial network effects and revenues might take off only slowly, then increase more drastically when a critical mass of users has obtained the service, and finally level off as the market reaches saturation.

Similarly, the frameworks presented here are very simple for the sake of transparency and because we want to present a new application of a tool that has previously been applied to other problems in the most straightforward way possible. The parameter θ, for instance, has been treated as a constant here (with the exception of the case where additional equipment on a satellite could lead to an increase in θ), but it is easy to imagine that, as technology progresses, θ can be improved as well, which will decrease the vulnerability of people and economies to disasters. A dynamic version of θ is, therefore, another possible extension that could offer interesting insights.

[10]There are several numerical implementations that all have their specific advantages and disadvantages depending on the application. We have chosen Monte Carlo simulation for reasons of computational efficiency and because we wanted to experiment with different processes, but the results coincide with those obtained when using partial differential equations.

[11]This would be different if we allowed for correlation between the two benefit streams. In the application at hand, however, we did not see a reason why such a correlation should exist.

[12]With "cases" we refer to the number of simulations here.

[13]A more elaborate model should take into account other factors (e.g. associated with the development phase or political issues) influencing the launching decision.

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References

[1] Harris R, Browning R. Global monitoring for environment and security: data policy considerations. Space Policy 2003;19:265–76.

[2] Dixit A, Pindyck R. Investment Under Uncertainty. Princeton: University Press; 1994.

[3] Organisation for Economic Cooperation and Development. Information and Communications Technologies—OECD Information Technology Outlook 2006.

[4] Macauley MK. The value of information: measuring the contribution of space-derived earth science data to resource management. Space Policy 2006;22:274–82.

[5] Peck SC, Teisberg TJ. Global warming uncertainties and the value of information: an analysis using CETA. Resource and Energy Economics 1993;15:71–97.

[6] Nordhaus WD, Popp D. What is the value of scientific knowledge? An application to global warming using the price model. The Energy Journal 1997;18:1–45.

[7] Fuss S, Johansson D, Szolgayova J, Obersteiner M. Impact of climate policy uncertainty on the adoption of electricity generating technologies. Working Paper 2008; International Institute of Systems Analysis.

[8] Lave L, Apt J. Planning for natural disasters in a stochastic world. Journal of Risk and Uncertainty 2006;33:117–30.

[9] Khabarov N, Moltchanova E, Obersteiner M. Valuing weather observation systems for forest fire management. Systems Journal, IEEE 2008;2(3):349–57.

[10] Moltchanova E, Khabarov N, Obersteiner M. Value of observations for building efficient earthquake rapid response system. Working Paper 2008, International Institute of Systems Analysis.

[11] PricewaterhouseCoopers. Inception study to support the development of a business plan for the GALILEO programme. Tech. Rep. 2001, TREN/B5/23-2001.

QUANTIFYING BENEFITS OF KNOWLEDGE AND INFORMATION

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(Working paper, at present not suitable for publication)

ABSTRACT

The main objective of this paper is to investigate possible ways and methods how to assign generally accepted concepts of value to the outputs of the research and scientific projects and organizations. The paper intends to provide assistance to readers interested in overall societal impact of the scientific and research knowledge and information. He might be a research project planer, project evaluator, or scientific organization manager.

Scientific and research projects are usually publicly financed, and they are approved by formal processes. In this work we consider two type of the assessment processes. The first is a process named the cost benefit analysis (CBA). The second investigated assessment process is project reporting through the project assessment rating tool (PART) designed and promoted by the OMB office of the US government.

The assessment process of the research impacts should be structured into three phases. In the first phase we identify the impact areas and the objects impacted by the scientific and research information. In the second stage we should capture the impacts and apply the valuation methods on these impacts. The methods should be closely related to the standard assessment or accounting methods. The third phase consists of inclusion of the uncertainties in both impact processes and the value realization processes.

Similar structure of assessment process could be found within the cost benefit approach. In addition to the CBA literature the most suitable models for the carrying out the first phase we found in the field of the knowledge management, the organization theory, and the publications related to the management of publicly financed research institutions. The applicable methodologies for the phase two we identified in the field of financial and managerial transfer pricing methods and in the field of intangible assets. For the third phase we limit ourselves to use the ideas from the accounting of intangible assets field only.

Similarly, like the cost-benefit analysis the output of our three-stage impact analysis should be suitable for decision processes too. Therefore, we should assess several types of value. On the benefit side, we should determine, so called, use value of the research knowledge which is the value summed up over some set of users and period of time. The second type of the value should be close to the investor value standard, which is the value, which accounts for all types of uncertainties. On the cost side, we should try to

determine fair or market value, under which research knowledge could be hypothetically obtained on the market.

CONTENTS

1. INTRODUCTION (ROUGH DRAFT)

This work is primary motivated by the 7th European program benefit evaluation project GEO-BENE sponsored by EU and carried out in relation with the GEO institute. The GEO institute is a center, which globally coordinates activities of various earth-related scientific and research institutions located worldwide. The main purpose of GEO-BENE project is to evaluate the widest range of societal benefits of joint research output of cluster of agencies organized around the GEO institute.

This cluster of institutions produce wide range of intellectual output ranging from massive datasets of modestly structured data like those important for the local weather forecasts to more structured information like recommendations for farmers, fishers, public health and security institutions. They also produce variety of scientific and technological knowledge in forms of journal publications and scientific books which are intended to impact entire field for significant period of time.

Evaluation of benefits of intellectual output of such a wide range should not be considered as an easy and quick task. Just the opposite, the task seems to be so complex that even before looking for the suitable methods the we have to identify firstly the scientific fields which could be related to it. Naturally, we identified cost/benefit analysis techniques (CBA), which has become a common technique for evaluation of public sector investment. Unfortunately, after brief review we decide to extend out search for suitable methods to other related fields. Within those fields we try to find common grounds with our evaluation project, to identify similarities in investigated objects and possibly to extent and transform the methodologies into form suitable for this area.

In addition to CBA, we investigate literature dealing with GPRA act and especially procedure for project evaluation PART. From this point the we survey the knowledge management field, economic appraisal methodics, the decision theory, design of organizations. We would like his article to be seen as a source of information for analysts evaluation he project of GEO cluster scale but also analyst evaluating a single-field oriented project or just a not-difficult-to-read paper for any person dealing with scientific and research project evaluations.

We try to provide certain framework to analyst in the following three steps of analytical and appraisal process:
1. to provide a guide how to identify area of possible impacts from the widest range.
2. to provide models how the research knowledge & information enters organization processes and the way it alters organization output.
3 to use an appropriate economic methods to value or benefits of the impact.

We should note that under the term impact we see impact defined in PART 3.1, which is termed *the ultimate output*, whose value can be measured by commonly accepted economic methods.

In he third part we enrich ideas how the knowledge reaches society found in literature related to GPRA/PART by models and diagrams found in knowledge management books.

In order to materialize its societal benefits the intellectual output must reach the world outside the field of scientific institutions. Our work shows models and schemas how the research output is channeled to the surrounding society. The outside environment, where benefits are supposed to materialize, are coarsely structured into the sector of the individual recipients in public, commercial sector and the sector of political decision makers. We are aware that great part of intellectual output is actually intended for another research or scientific institution and that these benefits could not be depicted in the manner suggested above.

The abstract models and schemas mentioned above is a necessary condition to start thinking about societal impacts and surveying them. The survey, on other side is a necessary condition for analyzing benefits, which could lead to their proper quantification.

In the beginning of our work we summarize works done in benefit evaluation by the leading research institution like DOE, EPA, NHI. In the recent years these agencies are under increasing pressure from the US governmental financing institutions to precisely measure efficiency of their activities. This is probably reason why they seem to be, at least in our opinion, the most active in this field.

In valuing research knowledge and information as any other entity we must distinguish between the process how and where the knowledge and information is used from the second perspective- what value the knowledge and information creates in the process.

Knowledge management and organization theory fields provide basic schemas into the knowledge development and application processes.

~~Value of information in decision proceses and in decision theory is outsketched in chapter 5.~~

~~Simple model for assesment of benefits from information-like-entity is given ich part 5. Assesment model is based on valuation method of intangible assets.~~

~~In the chapter 6 we try to discus the possible ways how to assign benefit to an information when the benefit itself is a result of joint action of the information and other part of a system.~~

In chapter 7 we would try to pin-point holistic view on societal value of research institution, where continual decisional process is important not a single output. Concluding remarks are given in the last chapter.

This work does not intend to give the exact procedure how to evaluate knowledge benefits with the present established economic methods or by their close analogies. Our intention is more less to give a guidance how to determine conditions and parameters which enable knowledge benefits be surveyed, quantified and evaluated. The paper tries to point out basic economic thoughts to project evaluators and decision makers in scientific field and we believe it will fill a certain void in the present literature.

The work is full of diagrams taken from various fields. All these should serve to form the most solid base for capturing the intellectual output processes.

The evaluation of benefits of public sector investment has been a standard part of public decision-making process for a long time. The established procedure of evaluation is named cost-benefit analysis (CBA). Basically cost-benefit analysis method attempts to estimate entire costs and benefits of investment under consideration using surveys or drawing inferences from the broadest range of impacted areas. This procedure is widely used on large scale public projects like motorway construction, *povinne ockovanie* and others. We suggest that from the viewpoint of policy decision maker it seems not unreasonable to apply similar analysis before approving funding for a particular research project.

In order to apply an analogous procedure like CBA method some principal questions in tracing benefits and economic impacts of knowledge &information must be addressed. The key difficulty is the method how to determine value of an entity like knowledge or information. Usually there is a little direct information about market value of the knowledge-like-entities available because the value is usually deformed by government interventions which occurs in various production steps. Information&knowledge entity could behave like one-time-use commodity or more like an asset, which releases its benefits or economic value over a long time and space period. One day forecast might release its benefits to local community and only within relatively short time period and within a few type of decision processes. On other side the developed method of fertiliznig soil, or invention of the transistor might have societal impact on almost unlimited time and space scale.

We believe, that basic ideas and approaches found in the present economic evaluation methods are, at least conceptualy, applicable also to benefit measurement processes. This is why, in addition to survey of published knowledge impact models, this paper uses schemes behind established economic evaluation methods for tracking non/monetary benefits of the outputs. ~~Moreover, we do not focus primarily on the capturing of the uncertainties whether or whether not project's results will be achieved, in spite of the fact that this might be often the most crucial factor. Main intention is to help decision makers to determine and quantify impacts and benefits of the expected results declared in the project unde evaluation.~~

The first phase we support a basic societal impact flow chart. This flow chart is supported by the models used in knowledge management field linear and cyclic models of knowledge creation and application used in knowledge management theory. These societal knowledge impact flowcharts has been used in practice by the work NRC documents as way to illustrate impact of production of large research agencies as EPA and NHI? The knowledge users are separated to the three distinct categories. The separation is suitable due to similarity of methods used in later stages.

After identification of the groups of individuals and the set of public or commercial organizations the knowledge impact should be studied in details inside the organization processes or the group. Theory of organization provides a guide how organization structures into hierarchy and what type of knowledge is used. The theory can distinguish information into categories like value-related information and physical type of information. Further more the departments can be classified according to the type of information they use. We envisage two distinct categories of information application, the operational processes, and the support of strategic decisions.

The detailness of the first phase depends on tools and methods we are going to use in the second value measuring phase. Accounting methods usually quantifies the value in more less direct way from the values available on the free market. The obvious reason for that is the position of the free market in the society, and therefore a source of their nominal value.

We do not form the methodics in the form of strict rules,
Our proposed method of appling accountant rules in decision process seems to determine value of information more realistically than normative VOI.

2. GPRA, PART, OMB AND RESPONSE OF RESEARCH AGENCIES.

In order to increase budget spending efficiency US government enacted in 1993 Government Performance Results Act [GPRA93]. This act requires all agencies funded by US government to restructure the way they report their outputs. Research-like institutions like Environment Protection Agency (EPA) or Department Of Energy (DOE) was also affected by this act.

In order to improve the reporting process, several years later in 2002, the Office of Management and Budget (OMB) has developed a special tool for project assessment called PART. PART is a questionare, which evaluates the project according to questions organized into several categories [EPA08]. Project purpose and category is weighted by 20%, strategic planning category 10%, program management category 20% and finally results and accountability category is given the weight of 50%.

According to the report [EPA08] the most difficult and inovative part in the project evaluation is to develop so called *project efficiency measure* based on ultimate project outcomes. OMB distinguishes between project outputs and the project outcomes. Project outputs refer to the internal-like activities of the program. The project outcomes define as intended broader results outside of the program. As an example of the measure of the project outcomes the OMB office gives number of lives saved or impact on health statistics.

Report elaborated by EPA [EPA08] suggests that the knowledge and information in forms of articles, books or trained personals are classified just as outputs of projects. The ultimate outcomes should be measured by metrics, which are based on more widely accepted societal values. The measure defined like number of reports produced is certainly reasonable to monitor program activity, but if we intuitively feel, that if their readers remains mostly within the particular project they could not serve as a measure of external project outcome.

OUTCOMES OF THE PROJECT AND THE ORGANIZATION MODEL

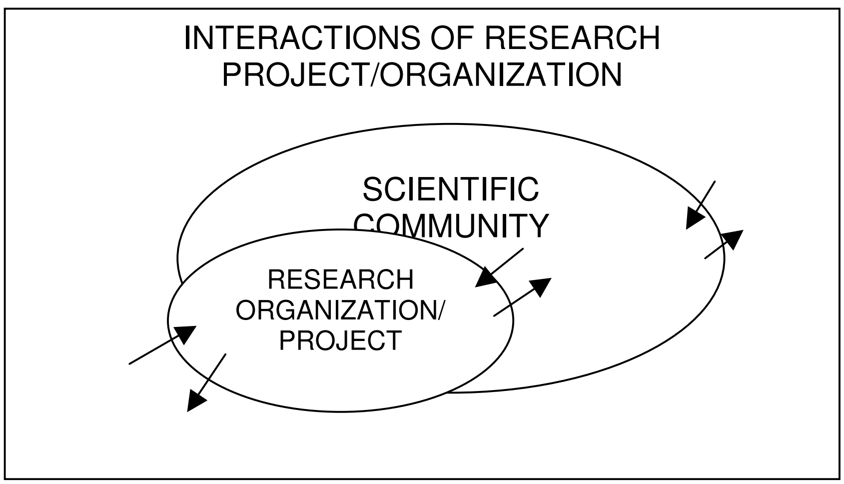
In our work we will consider evaluation of relatively large research projects, which has granted large resources through a extended time period. We could assume that this type of project could be treated as a temporary organization carrying out the research. This assumption allow us to treat research projects and research organizations in similar way.

The assumption enables us to model the interaction of the research project with the outer society through the approaches elaborated in the organization theory. The organizational theory defines organization as a goal directed societal unit with identifiable boundary [DAF98]. The concept of the organization or project boundary in the societal space is crucial in order to describe its interaction with the society. Through this abstract boundary projects and organizations receive inputs and returns outputs. Because the movement through the boundary occurs within time period the process is often described as a flow. The careful examination of input and output flows seems to be the first assumption to carry out the project assessment.

RESERCH PROJECT BOUNDARY

In the following we are going to depict how the project interacts with the outer environment. We separate outer environment into the two parts: the broader scientific and research community and the rest of the society. From both parts the research projects and organizations receive inputs and return outputs in exchange.

From the society receives economic and human resources, from scientific community receives basic knowledge, skills and data. In exchange, the research project and organization return outputs. The first type of outputs reaches outer society and it is utilized by the non-scientific organizations and the public. The second type of outputs goes to the scientific community and utilized by other projects.



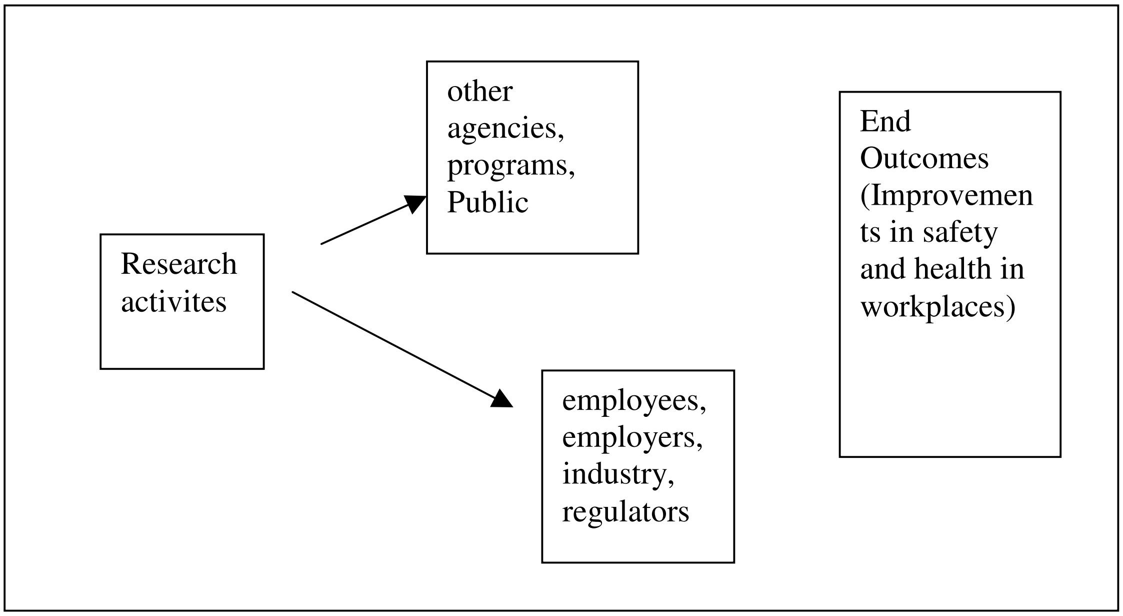
Flow of outputs directed to the scientific community can significantly contribute to the societal outputs of other projects. Many project planners consider the output to the scientific community to be primary outcome.

According our impression the Office of Management and budget would like to monitor the output and the input flows, and moreover, they wants to see the economic values assigned to them. In other words they would like to understand and control the value flows in a similar way like managers of big corporations do. Those corporations consist of clusters of relatively independent units with such diversified production that value flows monitoring could be the only achievable managing method.

Assessment methods discussed in this paper are quite but for to sake of paper simplicity, in the following we prefer to concentrate on measuring value of research and scientific outputs which are directly used by the society.

RESEARCH KNOWLEDGE SOCIETAL IMPACT MODELS

During recent years the research agencies have made an effort to evaluate impact of their research activities in agreement with the project assessment tool PART. The outputs has been structured into the logic model in [EPA08],[NRA07] and schematically could be depicted as in the following figure:



In their work Clark and Holiday [CLA06] describe the knowledge flow between the entire scientific community and the knowledge adopters in the similar manner. They propose to bridge a gap between these communities by the creation of a virtual boundary organization which is supposed to coordinate research knowledge production to satisfy adopters needs.

CLARK and Holiday

3. VALUATION PROCESS AND COST BENEFIT ANALYSIS

The value of the objects or service could be determined only when they are related to something which value is determined. Society has developed its own measures societal like health, safety or money. For example for the economists there is a significant difference between measuring quantity of some objects and quantifying their value. To determine quantity of objects investigating objects themselves is sufficient. But in order to determine the value of a object, the third party- the users of those objects, must be incorporated. The most fundamental way to determine the value of an object is to observe conditions under which the object is exchanged between producer and user under undisturbed free market conditions. In our cases this situation is quite rare, we have to find the value of our "objects" – the knowledge and information in indirect way.

FORMAL VALUATION PROCESS
In order to receive the most reliable answer to the question about the value of information we try to follow the formalized appraisal process, which is used by professional accountants.
Naturally the first steps of the process is to specify apraisal object. The preliminary scan of research institutions outputs suggest that their knowledge and information output could be categorized in the way which resembles categorization during apraisal of intangible assets. Into that category falls technological know-how, industrial designs, computer software and automated database, and last but not least human capital related assets as trained workforce [REIL99].
Reilly an Schweihs extends the topics of valuation of intangible assets to the situations of transfer pricing. The transfer pricing deals with the situation when the intangible assest like technology is transfered between economicly independent units of the same company in return of royalty payments. The transfer of intangible value resemble the situation when research institution transfers the knowledge to the commercial organization, and we use rely on this method later in the article.

THE PURPOSE OF THE APRAISAL
The purpose of the appraisal process describes the audience of the appraisal result and what kind of decisions will be affected. From the categories given by Reilly an Schweihs the main purpose seem to be information for strategic planning and management. This category suits well the decision making when financing research or scientific projects and seems to extend the cost benefit analysis, which is the method already in use.

VALUE STANDARDS
Before asking ourselves how to analyze the value of knowledge we should clarify the meaning of value. One has to note that the concept of value is far from the simple and we

need to narrow concept of value we are going to work with. In our work we suppose that value of an object is given by the relationship with the user subject. In formal appraisal process the question value to whom is addressed by the classification called value standard. For purpose of this work we can classify value of the object into three categories: Market related type of value, use value and investor value. The first type of value is related to real or hypothetical market price. The use type of value is related to the particular way of use of the object. Investor value of an object or entity is a value in relation with particular set of criteria.

APRAISER STANDARTS AND COST BENEFIT ANALYSIS

Our primary aim is to incorporate valuation of knowledge and information into cost benefit analysis. From the CBA analyst perspective we could associate the use values with a guessed demand curve. Benefits are then calculated as a simple integrated difference between values on hypothetical demand curve and appropriate costs.

In order to use within project selection process we need to introduce a time dimension. This is the point where the analogy of the investor value steps in. The knowledge as other intangible asset releases its value over a period of the time. But the future expected returns usually involve risks and uncertainties. This and other time related factors are accounted by inclusion of so called discount factor, which could be determined by several ways.

RESEARCH OUTPUTS AS EXTERNAL EFFECTS

The output of public research organizations do not address developed market of good. Therefore evaluation of direct benefits might be missing. They are disseminated for negligible cost and by companies are precevied as a form of exteranlities.(????) Therefore we can not use direct CBA benefit evaluation methodologies but we should assume that major value is realized through through these effects, often termed or spillovers.

Knowledge and information similarly like other intangible assets usually need another tangible asset in order to explicitly materialize their value. They are transferred to another subject, and only then we could observe measurable increases of value of output or decrease in costs.

REAL AND PECUNIARY PHENOMENA

There is a little doubt that spillovers should be included into benefits as long as they are related to the technical or real effects[Tef96]. What analysts should be carefful to distinguish these "real external" effects from, so called, pecuniary effects. The pecuniary effects are characterized by presence of redistributive phenomena. As a secondary project output might be the increase of market value of real estates; on other side the increased profit for the real estate owner is negated by the increased cost of the buyer, therefore the total effect might be close to zero.There is an concensus not to include these effects [Tef96].

TECHNOLOGICAL APPROACH TO THE VALUATION OF THE KNOWLEDGE AND INFORMATION

INFORMATION AS AN OPTIMIZATION ELEMENT
In this chapter we would like to introduce concept of value information as a mean for optimization of purpose directed behavior. A robot trying to pick some object inside a room spends much less valuable energy if it utilizes a visual information compared with the situation of random movement in the open space. In this simplistic example we could see the basics of information valuation scheme. To calculate the value of information for the one case we need to see how robot optimizes its work, trace the decreased cost. Then generalize the situation over larger set of robot object pickings. To make valuation complete wee need to consider value of the knowledge or skills which is embeded in robots visual decision algorithms, then we consider the fixed and variable cost of robot optical unit and information processing unit.

In order to evaluate value of information we do not need to know monetary value of energy and we can quantify the value of information liters of fuel and minutes of spared time. In certain situation this procedure is sufficient. ~~But when considering more complex cases we need to compare savings of fuel with the cost of optical and information processing unit we need to~~

A SUBJECT PERSPECTIVE OF VALUE OF KNOWLEDGE AND INFORMATION

It seems that relationship between the knowledge&information on the one side and the quantified value on the other side could be determined in relation to some subject. The subject utilizes the knowledge and information to achieve its goals. The subject might be a person, an organization, the living organism, or even a complex inorganic system, which exhibits a purpose-directed behavior within a varying external environment. (Analogy with the *use value* accounting standard)
The knowledge and the information can roughly imagined as the way, how the neural or electronic cells of the subject are set and organized in order to control its actions or alter the course of its actions. The subject might pursue a goal or set of goals, like satisfying its basic needs, its reproduction or building a capacity to pursue these goals in future. To each of its goals or steps in achieving these goals the subject attributes a level of priority, and this priority closely related to the concept of value.

The value of a goal can purely depend on the subject preferences, but there are classes of activities when the prime goal is to produce outputs that satisfies needs of other subjects. In the first case, the value for the individual could be observed by observing how subject prefers this particular goal over other goals. In the second case the outputs are usually exchanged within a broader community of subjects and the exchanged ratios could form a base for quantifications of output values. The value can be quantified directly in economic terms like number of hours or energy, or amount of resources that subject is willing to spend to achieve this particular goal.

INFORMATION AS A TOOL FOR OPTIMIZATION

After the identification of all goals and their priorities the next step is to identify the way, how the subject achieves them by its activities. Activities should be mapped perhaps onto some form of process diagrams or other type of schematics. Consequently, impact of the knowledge and information should be examined for each process. A single knowledge & information can affect the wide scale of activities and the wide scale of outputs. Analyst need to track down the ways how the knowledge & information affects the objects, actions and events which are taking place during the output production.

OUTPUT VALUE CHANGE DUE TO THE K&I

The easiest way how to valuate the knowledge & information impact on the process is to compare the value generated and cost needed by the processes before knowledge & information is applied with the output value generated after its application. If we subtract from this difference a cost of information application and adaptation we can get the number which could be attributed to the value of the information for the particular subject, activity and the for the time period.

The analysis can be elaborated according to expectations, case studies, or according to information application, which already happens in mass scale.

THE COMMUNITY VALUE OF INFORMATION

The concept of the "community value" can be formulated again before examining industrial human society. Once a member of a community has achieved information of skill it can effortlessly transmit it to the other members of community. It can be transmitted through the coping and learning. One of the fundamental characteristics of the knowledge & information is that once it is produced it can be applied by the members of same community subjects often with negligible additional costs. In economic terms the knowledge and information has often a great fixed and negligible variable cost. The simplest approach of calculation of the community value is to sum up all benefits for all users and subtract the production and distribution costs. This method is applied in cost-benefit method.

4. KNOWLEDGE& INFORMATION FROM THE ORGANIZATIONAL THEORY PERSPECTIVE

In order to understand the impact of knowledge and information in broadest sense, we need to understand how the society structures itself and how society structures its activities. Possibly the most important concept in this field is the concept of an organization. In the following we introduce a basic ideas of organizational theory.

DEFINITON OF AN ORGANIZATION

Here, we could rely on a strightforward definition of the organization, which can be found in textbooks [Daft p10]:
The organizations are social entities that are goal directed, deliberately structured activity systems with an identifiable boundary. Organizations are open systems which acquire inputs from the surrounding environment, transform them into something of value and export the result back into the surrounding environment and community.

In addition to this, the organization are assumed has a *deliberately structured activity systems.* Organization tasks are subdivided in sets of activities.

Reading the definition and notes above we can immediately see how we can determine impact of anything on the organizational output value. If we have perfect information both about the organization and the surrounding environment, we just examine the impact of additional knowledge and information on organization's activity system. By monitoring the impacts we could determine the change in organization output value or change in organization inputs.

CATEGORIES OF ORGANIZATIONS AND THE FREE MARKET

One of the most important societal entities is a regulated space for interaction among individuals and organizations. We consider relationship of the organization to the free market as a crucial for valuation process. The pricing mechanisms of the free market allow us to quantify the value of changes in the organizational inputs and outputs.

Therefore organizations could be classified into two different categories. To the first category belong the non-commercial institutions and organizations which have usually directly or indirectly delegated power and responsibilities about some collective societal issues. The second category is represented by the commercial organizations, whose course of actions are determined primarily by its inputs and outputs to the free market.

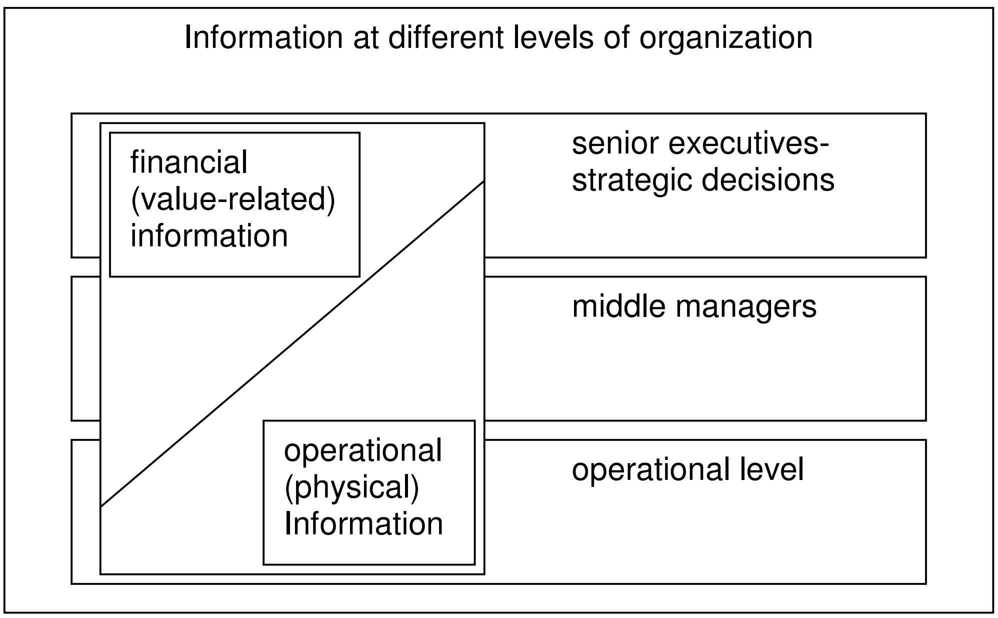
In order to map and to evaluate the impact of publicly available information it seems arguable to separate potential users into three categories: commercial organizations, non commercial organizations and users. These categories are very close to those suggested by W.Clark and L. Holliday (2006) in their knowledge-action supply chain model.

For each one of the three classes of users we will need principally different methods for quantifing impact of information on the output value. We concentrate on the evaluation of impact on commercial organizations because we expect that evaluation methodologies are the most elaborated just in this field. Then we try to apply the methods for the case of non/commercial institutions. We do not put much attention to the last category- the category of individual users.

TYPE OF INFORMATION AN ORGANIZATION HIERARCHY

Organizations are complex structures, the analyst needs at least an approximate guide where in the activity system he should look to find impact. There are several models of the information role in the organization theory. The most fundamental classification of the information seems to be according to the hierarchy of the organizations.

A. Atkinson in [ATK 95] suggested traditional information needs at different level of the organization looks like



Information is grouped into two fundamental categories- information about physical subjects and processes and information about value of these subjects and processes.

R.L. Daft [Daft] stressed that at the top level the organization information about external environment to make decisions. On the opposite, at the lower organization level information reflects the need of monitoring operations, information tend to be internal.

Another information classification scheme introduces Daft with Macintosh according to parameters called information richness and the information amount. The classification implies four classes of technologies, routine technology, engineering technology, “craft-like” technologies and non-routine technology. Routine technology is supposed to be used in the lower level of organization, so called non-routine technologies should dominate top level of the organization. The second classification scheme shows, that information might enter the organization also via the engineering departments or via departments using “craft-like” technologies like the buying of financial derivates.

5. KNOWLEDGE AND INFORMATION PROCESS CYCLES

MAPPING THE INFROMATION INTERACTION WITH OTHER SUBJECTS AND PROCESSES

In order to carry out the process of **evaluation of knowledge-like-entities** we need to identify them and then to capture in details the way they interact with processes which creates something of value. Another scientific field, which could provide us assistance, is the branch of the management science.

Management science has recognized importance of an explicit description of role of information and knowledge in various organizational processes long time ago. In the management textbooks the flow models or flow diagrams are recommended to depict the role of information. As the complexity of knowledge and information increased the new specialized branch of management science has been developed. The branch has received name the knowledge management.

Knowledge management authors claim that the field is a unique synthesis of other established areas like the organizational science, cognitive sciences, information sciences, learning and decision sciences. The field developed in close relationship with commercial enterprises. These field has developed in close connection to the business area so it is claimed to be capable deal with *the creation, capture, organization, access and use of enterprise’s intellectual assets* (Grey, 1996/Dal 5).

Necessary condition to carry out the process of **knowledge evaluation** is the proper identification, classification and structuring of the knowledge-like-entities. Knowledge management offers us several perspectives how the knowledge or information like-entities should be categorized. The first, perhaps the most basic categorization of this entites is categorization into three groups called the data, information and knowledge.

Knowledge management literature gives [DAV98][Daft304] the following specifications for these categories.

Data	*A set od discrete, objective facts about events, often the output of a communication channel.*
Information	*A message that alters mental image, ususally in the form of a document or an audible or visible communication*
Knowledge	*A mix of framed experiences, values, contextual information and expert insights. It originates and is applied in the minds of knowers. Often embeded not only in documents but in routines, processes, practices and norms*

The knowledge category is often divided to the explicit and tacit forms. The explicit form of knowledge is that which is usually codified in documents. The tacit knowledge is not. Tacit knowledge is something, which is considered not separable or difficult to separate from its owner- the trained and experienced person.

The knowledge accessibility could create another criteria for categorization. The knowledge, information and data could be put into three categories like public, shared and personal. Knowledge could pose plenty of other attributes like being factual or conceptual, predicative or descriptive or methodological.

The analyst should bear all these background categories of information in mind in order to construct complete description.

One might point out that economic, organizational and managerial literature see this subject from more practical perspective. For example, the engineers tend to pack data, information, and knowledge altogether into a *technology*, lawyers and accountants might see the technology or fragment of technology as a *patent*. The information flows through the managerial and operational information systems. Information then serve to support decision processes. Information might be purely related to the engineering problems or to the external environment.

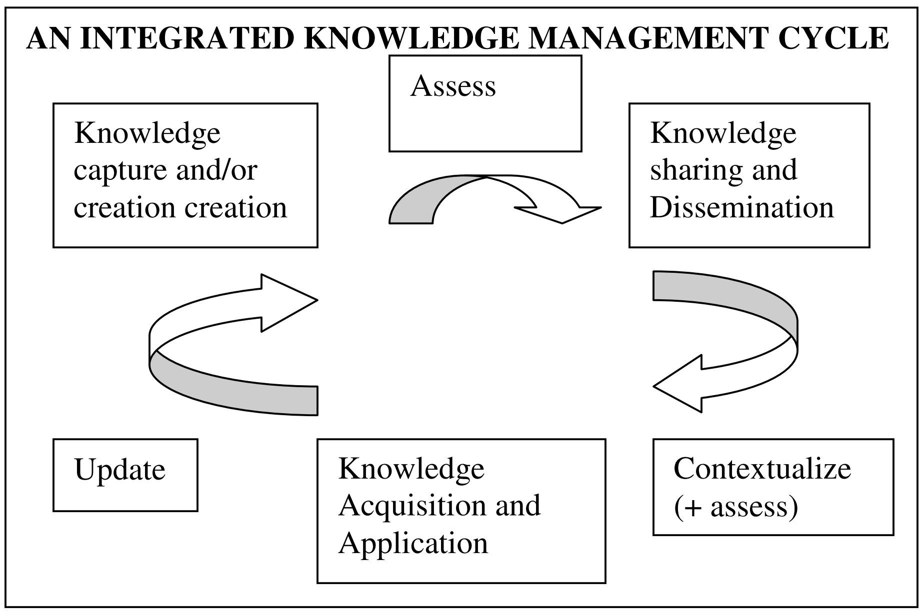
For the analyst these practical terms might be more applicable then those found in knowledge management field. On other side, the knowledge management models concentrates more on dealing with the human capital and model hold also for the knowledge propagation and application outside commercial organizations.

The next part of the chapter we demonstrate how to describe development and propagation of the knowledge-like entities in the time-spatial scale. The key concept for the description will be the concept of knowledge lifecycles.

THE KNOWLEDGE AND INFORMATION PHASES AND CYCLES

The categorization of knowledge and information is not sufficient in understanding the way of interaction of knowledge-like-entities with surrounding environment. describing the complexity of interaction of knowledge and activities and subjects.

In our opinion one of the brightest ideas of the book [Dal] was an introduction of so called integrated knowledge management cycle. Author integrates time-spatial phases of the knowledge creation and propagation as follows:



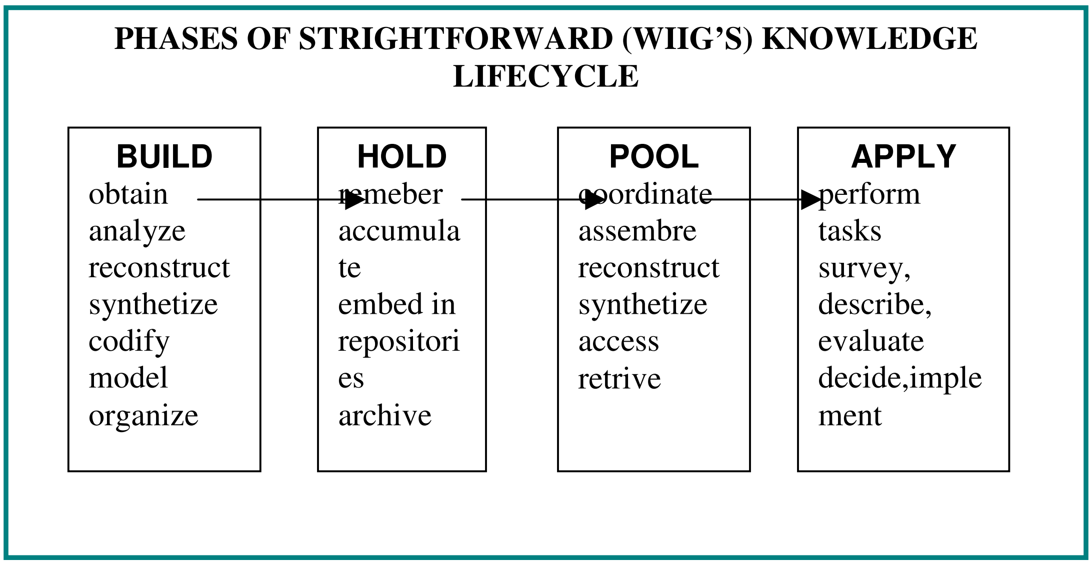
The integrated knowledge lifecycle model is a synthesis of other models. It identifies three different stages.

Author sees this model as an abstraction of knowledge lifecycle within an organization. In spite of positive features, the integrated cycle is subject of simplifications. As the most important we see localization of assessment process exclusivelly between knowledge dissemination stage and knowledge creation stage. Transitions between stages are always connected with a decisions and assessment is always a part of it. We believe that true knowledge valuation is possible only through the feedback from the application stage. In next chapter we solve this problem by superimposing the value flow model over these models.

From the perspective of our work we might find situation where cyclic or spiral nature character of the model is not considered to be important. This is why we consider the simpler the Wiigs knowledge lifecycle sufficient.

STRIGHTFORWARED KNOWLEDGE MODEL

Literature offers other models of knowledge lifecycles, which could be combined into the integrated model mentioned above. Strightforward knowledge model model describes knowledge lifecycle as a strightforward proces from its creation phase to its terminal phase- to its value realization application phase. The schematics of the model



The strightforward model consists of four stages. The model resembles previous cyclical one disintegrated at the phase called knowledge update. The stage of sharing and dissemination is separated into two stages knowledge archivation and then the knowledge retrieval. The keywords should help analyst to better identify stages in practical situations. The Wiigs model places the valuation at single stage. We consider it as an oversimplification and value related aspect are present in all stages.

CHAPTER CONCLUSION

This chapter gave a basic introduction about the basic schemes how the knowledge and information is created, disseminated, and applied. Knowledge management theory concentrates on processes within a single organization but we believe that basic principles should hold also in broader societal range. This quite natural assumption allow us to use knowledge management models as a starting point in depicting impacts of any knowledge and any information.

We should note, that similarily as in other management areas the subjects of information and knowledge and their life cycles could be approached from two perspectives which always exists in paralel. The first perspective we might call a proces perspective the knowledge and information is studied in relation to the activities and subjects present in an organization or investigated environment. Time and spatial characterisitics are also *put into relation with these characteristic of other subjects and activities. The second perspective is a perpsctive, when we investigated all these relations and processes from a value perspective or from a perspective of its costs and incresed values. Mentioned perspectives are strongly intertwined, and in spite of that it is not explicitly stated, detailed description of knowledge creation propagation and application is a crucial moment in determining value of information.*

6. FROM KNOWLEDGE MANAGEMENT LIFECYCLES TO THE KNOWLEDGE VALUE CHAIN: MANAGERIAL ACCOUNTING MODELS

Management accounting is the field which judges all organization activities from the perspective of their cost and their contribution to the value of final product. Practical reason for this is to achieve the highest possible profitability. In order to understand the basic economics of knowledge and information processes we suggest superimposition of their value-focused models and methods on the knowledge lifecycles models found in knowledge management theory. In the following we put our attention on *value chain model*, *organizational architecture model* and managerial transfer pricing methods.

Depicted Wiig's sequential knowledge life cycle model seems to be extremely suitable for demonstrating tight analogy with value-focused models used in managerial accounting field. Within the Wigs model the cycle starts with knowledge creation and ends with the value realization [Dal44].

This model of knowledge lifecycle resembles model of a product creation in a company suggested by Michael Porter's value chain model. Value chain model is a managerial model of a company, which increases company's competitivness thorough the carefull and accurate cost management. For the sake of management the production process is disintegrated down to the elements named "individual value activities". By the term "individual value activity" is meant a distiguisheble part of company's activities with distinct technologies and relatively distinct economics.

Author of this model does not give a guide how to determine value created within each of these units and exact determination does not seem to be in central focus of this approach. Anyway, we consider this model for our work important because it explicitlly suggest that the value creation and realization happens in a sequence of "value activities". These activity blocks could be determined, and their individual contribution to the value creation depends on the final value experinced by the end user. We consider this value chain model as a bridge between knowledge management cycles and standard managerial accounting techniques mentioned in the next paragraph.

MANAGERIAL TRANSFER PRICING AND ORGANIZATIONAL ARCHITECTURE MODEL

At the end of the chapter about knowledge management models we have suggested that it is reasonable to believe, that those models are also valid for any cluster of institutions. If we continue in superimposing (exploring) managerial accounting techniques on knowledge processes we find immediatelly a striking similarity between cluster of scientific institutions exchanging knowledge and information and cluster of companies organized in big ususally multinational company exchanging products and servicies. In both cases products have no clear market value.

Management accounting has been dealing with this subject for a quite period of a time. Actually, for this cluster of weakly coupled companies they developed a managment model called *organizational architecture,* which is purely based on accounting methods and decision rights assigment. Ignoring the model details, the multinational company is divided to distict units called cost centres, profit centres or even investment centers. Performance of each centre is determined by measuring cost of inputs and value of outputs. Measurement is difficult because the profit ctnter's inputs and outputs are actually intermediate products within larger corporation and might not have a clear market value.

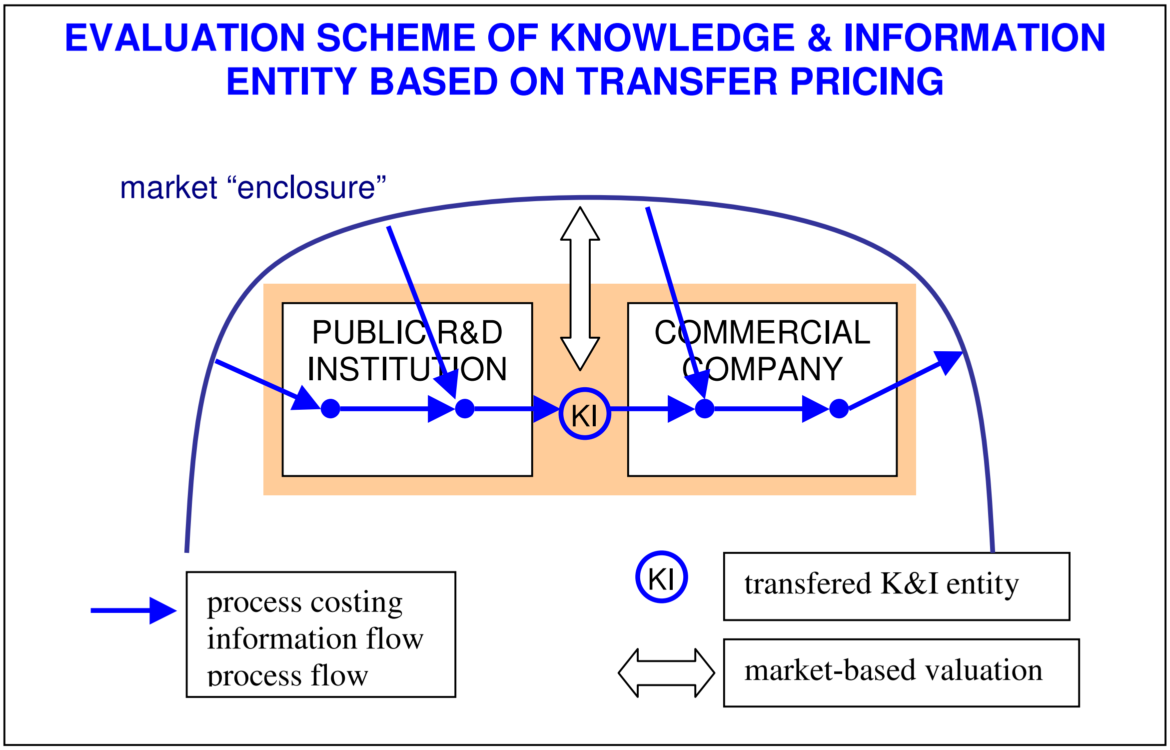
In order to resolve this problem a set of accounting methods called transfer prising methods has been developed. Literature gives several classes of methods which two of them seems to be the most signicant. Those classes are market-based transfer pricing methods, and cost based transfer prices. Marked based methods derives value of intermediate product from presence of similar product in the market, the cost - based methods give the intermediate product the value according variable or total cost plus some percentage of markup. The methods are adapted to assess the product value also in situations when exact informations might be not known even to cost or profit center managers or is distorted by them to preserve their interests.

GENERALIZED TRANSFER PRICING METHOD

We consider managerial and financial transfer pricing methodologies as universal patterns accepted by economists for calculation of value of entity which is subject of exchange or transfer between two independent economic units. The value of transfered entity could be determined even in absence of similar product on the market. Transfer pricing methods are extensively used and they are well documented and examined. None of them should be considered as superior. The market based pricing might be missleading when transactional cost of using market is significant. On other side the cost based methods thoroughly ignore problem of inefficiency and incorrect fixed cost allocations.

In the folowing paragraph we will exploit the transfer pricing method in order to survey the basic set of requirements which should be met to make possible the determination of values of entities like knowledge in a sound way. As the simplest possible example we depict the case of public research institute providing data or som knowledge and information package to a commertial company.

For the sake of this study we imagine these two units merged into fictious larger enterprise. Just to make this construction more plausible we mention that concept of enterprise enlarged of its suppliers is sometime called the extended enterprise, and resembles japanese kereitsu. This merged couple is again, as any other organization surrounded by outer environment. Free market is also a part of the surrounding environment; organization takes from it inputs and returns ouptut. [DAFT]



This is depicted on Figure 5. We should note that information production, transfer and aplication line could be compared with knowledge lifecycle models given in knowldge management field. Left part of process flow line in figure above actually represents abreviated strightforward (Wiig's) model of the knowledge lifecycle discussed before.

DETERMINANTION OF VALUE OF TRANSFERED K&I ENTITIES

Let us investigate an example depicted on Figure 5 from managerial accountant perspective. Let us suppose that the commercial company earns profit which is a difference between costs of inputs and value of outputs. Then the comercial company decides to use information and data produced by publicly financed research institution to increase efficiency of its operations. After the application of information the production cost Cc is reduced to Cc' and/or the value of output Vc is increased to Vc. The public research institute has full cost Cp associated with K&I package. To answer the question what is the value of the information and information managerial accountat would apply some of the transfer pricing methods. As the first he might examine market based method and he could try to determine the value or range of values by identifying the set of most similar K&I transfers which already happened on the market. In the case that there is not enough market data or market is distorted or absent he could continue with the cost-based transfer pricing analysis. The cost based methods would give a value based on fixed or variable costs plus an percentage of comercial company's markup or increased markup.

Determination of the proper markup percentage might be supprisingly difficult. Probably the best way to find the value is to continue with profit split transfer pricing methods like the "comparable profits method" (CPM). These methods might reflect a different level of risk taking of each individual party. Or they might put stress on a fact that routine technologies usually add lower value into the overall profitability in comparison with non-routine technologies [TRANS]. Which part of the total profit should be attributed to the particular economic units are affected by many factors and they are summarized later in this article at the chapter devoted to the intangible assets.

SCIENTIFIC OUTPUT FOR DECISION MAKING

Slides: Scientific output for decision making

7. VALUE OF INFORMATION IN DECISION THEORY

Information could materialize its value only when it alter some processes which could be judged by economical categories like costs of inputs or value of outputs. Decision process is considered as the process, where information value can be measured. It seems that any rational alteration of any proces due to information can be called a decision. This could explain the fact that prevailing amount of literature relates value of information to the decision theory.

The decision theory describes clasifies their approaches in various ways. Daft [DAF86] classifies approaches to the as rational or bounded rational. As a second clasification scheme he uses clasification according goal or technology uncertainties. Lehto [LEH08] introduces clasification decision theories to normative, behavioural and naturalistic. Beroggi [BER99] compares normative and decriptive decison models.

To get basic ide of the rational decision making proces, we introduce basic schema of rational decision making on the following picture.

RATIONAL APPROACH TO DECISION MAKING

Problem identification		Problem Solution
1. Monitor the Decision Environment 2. Define the problem 3. Specify Decision Objectives 4. Diagnose the problem	→	Develop Alternative Solutions 6. Evaluate Alternative Solutions 7. Choose the best Alternative 8. Implement the chosen alternative

In order to estimate value of information in the decision process the analyst should construct understand the phases of the decision making, actors and external environment. Fundamental steps of analytical approach to descriptive and normative decision processes are discussed in [BER99].

ECONOMICS OF DECISION PROCESS

As any other organization process the decision making process has its cost, output value and efficiency. Especialy for the operation level or for repetitive and programed decisions the efficiency of decision processes has been studied long time ago. Efficiency of this process is the principal economic driver for the deveopment of various decision support system for low and middle level managers. In this type of decisions the economics of reduction of uncertainty can be monitered and demonstrated. If an aditional information increases number of correct decision events (under certain conditions, which will be mentioned later) the information value can be attributed to that.

Non-programmed and non-repetitive decisions, which are again happening in the uncertain environment, have their measurable economical aspects too. The economical constraints of the decision process actually may be one of the most important drivers for the preference of bounded rationality approach to decision process over the systematic rational approach. Time pressure, unclear preferences, uncertainty in techniques have led to development of methods like incremental or adaptive decision making, coalition formation or garbage-can method.

Determinantion of the output value for non-repeteitive decision process within uncertain environment is hampered by its uniques. The value of the decision process output cannot be easily empirically determined as an averaged success rate of the repetitive situations. The problem is usually unique, therefore a rather different way of description of uncertainty has to be introduced. The uncertainty is then described by introduction of the probability as a measure of state of knowledge. This kind probability often is termed the Bayesian probability. Value of information is considered not against some empiricaly measurable averaged value of decision proces but more like a measure of guidinance for decission makers to carry out the best choois possible between alternatives.

In the real world, the non-repetitive decisions are carried out by politicians, managers, and individuals and stand in the centre of many studies[Ber99]

The value of decsion process output is naturally measured in the different way if decision is done by management of commertial organization, individual or politicians.
In the situation of undistorted perfect market and commertial organization the economy of top managerial level decisions are evaluated by buyers preferences.

At the end of this paragraph we coul say that the importacce of ekonomization of the decision proces has been realized some times ago.Lehto and Buck in [LEH08] say that in the recent years has been recognized, that in real situation people rarely use classical decision theory to make decisions. People prefer to select different decision strategies depending on their own experience, the task and the decision context. Moreover authors stress the fact, that *several of the [decision making] models also postulate that people choose between decision strategies by trading off effectiveness against the effort required.* This is actually suggesting, that decision often starts with economical consideration and optimalization of the decision making processes, which is the topic we investigate in this chapter.

EXPECTED VALUE IN THE CLASSICAL DECISION THEORY

Classical decision theory usually describes the decision processes by the models like decision tree model, influence diagram model or decision matrix model. These models capture and organize data for the core phase of the decision making. The phase is refered to in previous paragraphs as "*choosing the best alternative*".

In order to carry out this phase efficiently four different sets of elements have to be determined. Those sets are: the set of potential actions, the set of events or world states, a set of probabilities for each combination of action and event and a set of consequencies. Each of the alternatives are evaluated with respect to the accepted criteria. Under the presence of uncertainty the evaluation must be done with respect to one or more possible scenarios. The uncertainty enters the evaluation in the form of probability. Therefore adjective expected is included before the word value, because the value represents only an avarge over larger sets of similar decision situations. Details of normative decision theory can be found in [BER99],[LEH08].

VALUE OF INFORMATION IN CLASSICAL DECISION THEORY

The value of information concept has been in introduced in managerial and economical textbooks long time ago [BER99], [CLE96], [KIR02], [KRA99], [TER07]. The value is determined in the framework of normative approach to decison processes. The basic idea for determinantion of value of information is, that information eliminates some level of uncertainty of decision steps in the decision processes. In the case of the decision tree model, buying and additional information creates an alternative decision path usually with higher expected value. The difference between the original expected value and this higher expected value with is considered to be the value of information (VOI) or the expected value of information.

The method of calculation of expected value of information is well established but many authors rise questions how this value should be used in practice. D. Hubbard [Hub2003] expresses an idea that this type of value represents an *extreme upper bound* for the effort attached to the aquisiton of the information. He suggests a rule, that in practice only 2%-20% of the calculated value should be spend at the highest for this information. Another doubt about VOI practical applicability comes directly from C. Kirkwood [KIR02] textbook example. For the sake of realistic ilustration he chooses a dialog between analyst and manager discussing whether it is reasonable to pay a consultant 2% value of the calculated value.

COSTS AND BENEFIS OF THE INFORMATION

Economical aspect of the information acquiring processes has been briefly discussed by D. Samson [SAM88]. The meaning expected value of information (EVI) simply attributes to the benefit of information. He suggests, that we should invest such amount of money into information acquisition process, which maximizes the difference between information benefit and information cost. The optimization is ilustrated by the case, when benefit of information increases with the extent of information gathering activities. The aqusition process is described by a rising curve, and the cuve of information benefits is convex and has a general tendency to reach asymptoticaly the level of benefits of perfect information (In [HUB07] this curve is termed as EVI curve). Cost of information gathering activities is supposed to increases in proportion to their extent. Due to the shapes of cost and benefit curves there is always an extent of information related activities, where the net gain could be maximized. Unfortuantely, author gives no indicative data about what fraction of VOI could be the optimal value for the investment. Ilustrative diagram indicates value around 40-50%.

NORMATIVE VALUE OF INFORMATION AND ACCOUNTING METHODS

Two percent level of the VOI for an investment is one even two orders lower that the calculation based on normative decision theory. On of the reasons might be, that the applicability of normative decision theory is limited due to presence of uncertainties not well captured by the decision models. A study quoted by R. Daft [DAF86] found that thirty of thirty three decision problems are ambiguous or ill-defined. This is why the range of 2%-20% investment rule might actually reflects reasonable limits for case of a sequential investment strategy.

Another doubt about aplicability of VOI comes from the fact that the expected value is in principle and uncertain value and we should judge our spending according to the, so called, certainty equivalent, which should be lower. This lower but certain value is in financial accounting often termed the “present value”. The adjective “present” is chosen probably because within the investment comunity the uncertainty grows primarily with the time lag between investment and future returns and therefore meaning of the word “present” is close to the meaning “certain”.

Applying common accounting principles to the decision processes like transfer pricing might shed an additional light to the aplicability of VOI. Additional information increases the quality of final decision process output. For a while, let us we imagine that the decision maker and information provider together create a fictious extended enterprise. Information is a kind of intermediate product transferred between two parts of the enterprise and managerial transfer price methods should hold. In that case the value should be determined, for example, according to total cost plus a percentage of certainty equivalent of expected profit value.

Application of probability estimations in classical decision theory might be also source of a doubt. For example, suppose we have investment decision problem and the only credible information is, that the return value is less then hundred euros. Some of the analysts would model similar situations by the uniform probability distribution of returns between zero and one hundred. But no rational investor would invest under these circumtancies forty nine euros in order to earn one euro in average. The investor needs additional information at least about averaged return. Moreover in that situation, he needs reasonable data about the previous investments cases in order to assure himself that the assumption of the uniform probability of return is applicable also in his case. In opposite case he would lower the investment, perhaps again to the 2% of expected return.

8. VALUE OF INFORMATION FROM THE ASSET PERSPECTIVE (KNOWLEDGE/ INFORMATON AS AN INTANGIBLE ASSET)

In spite of the fact that the concept „value of information“ is relatively frequently used, we did not succeed to identify robust and unified set of approaches for its assessment.

In the following we are going to investigate the middle line in our value stream diagram [Fig. 2]. The output of public scientific institutions reaches commercial organizations. These use as an input and use it in order to efficiently deliver her products.

Area of business and accounting is the area which very reach on the most robust and reliable valuation methods for any kind of situation and for almost any kind of valuation-capable entities. Methods are well verified and trusted by investors, businessmen and ordinary people. They are used for purchases, sales and other market transactions.
This area built variety of concepts like markets, goods, services and assets, which become part of everyday terminology.

Firstly in order to envisage the position of commercial organization form economic perspective we need to redraw the diagram [Fig.2]. We already mention that commercial organization like any other organization is surrounded by the enclosing environment. They acquire inputs, transform them and export the result back into the surrounding environment. To describe interaction of the organization it is extremely important whether the organization is interacting with the market non market environment. The situation is envisaged on the Fig.8.

In this picture, by the asset we mean almost anything which releases its value during certain time period, and usually enters the balance sheets of firm as an fixed costs. By the goods we mean something, that release the value immediately into product and it is value is usually included in the product as a variable cost.

Evaluators in the field of accounting, called appraisers, during value-determining process distinguish asset those that are tangible and those, which are intangible. Typical tangible assets are equipment, or entire production line; the textbook examples of intangible assets are entities like a technology, data processing system, or trademark
.
Entity under our investigation - knowledge & information produced by public research organization seems fit quite closely the technology example of intangible asset. In general, accountant's textbooks give several conditions, which should be met before any entity is declared as intangible asset. The entity should be clearly identifiable, have a legal existence, time of creation. Moreover, entity should be subject to the right of ownership and there should clear manifestation of this existence, like printed and signed contract. In order to apply accounting methods it advantegous to imagine knowledge & information in form of some applicable package.

Literature of Valuation methods do not give only procedure how to evaluate a particulatr asset, they give a plenty of hints actually how to identify through which interaction the asset releases its value. According to [Rei99] intangible asset has a value if the following two conditions are satisfied:

Firstly, in order for an intangible [asset] to have an economic value, it should generate some measurable amount of economic benefit to its owner. The economic benefit to the owner may be in the form of an income increment or a cost decrement.

…

Secondly, in order for an intangible asset to have economic value, it should potentially enhance the value of other assets[tangible or intangible] with which it is associated…. [REI99, p.9]

Appraiser science has several definitions of the economic value and strictly differentiate among them. Before evaluation process so called, "standard of value" is used. For our knowledge & information asset entity we apply standards like the use value, the investment value or the owner value.

BACKGROUND OF INTANGIBLE ASSET VALUATION METHODS

Generally there are three basic approaches for the asset evaluation. In the following we quote the definitions of all three:

The cost approach to intangible asset analysis is based upon the economic principles of substitution and price equilibrium (often called the competitive equilibrium price). These basic economic principles assert that an investor will pay no more for an investment than the cost to obtain an investment of equal utility.

The market approach is based upon related economic principles of competition and equilibrium. These economic principles conclude that in a free and unrestricted market, supply and demand factors will drive the price of any good (such as … intangible asset) to a point of equilibrium.

The income method is based upon the economic principle of anticipation (sometimes also called principle of expectation). In this approach the value of the intangible asset is the present value of the expected economic income to be earned from the ownership of that asset.

If the commercial organization on [Figure 8] takes the asset from the developed market all three methods mentioned above should converge to the same number. In the case of publicly produced research knowledge & information we can not relay on existence of any market. We can not assume even existence of any market of close products. This entirely excludes market approach to evaluation of research knowledge & information.

On the other side, we still can assume reasonably developed market on the output side of the company which utilizes the asset. Market on the output side can provide data needed for the income asset evaluation method.

OVERVIEW OF INCOME APPROACH METHODS

In the income approach method the value of an intangible asset is determined as the:

present value of the expected economic income associated with the ownership, use, or forbearance of that intangible asset. [REI p.161]

As before, we assume undeveloped asset market and in our calculation & data collection we focus only on income associated with the use of the [research knowledge] asset.

The income approach method consist from there components; 1. projected economic income decreased by all possible types of expenses, 2. estimation of time period of the income 3. method for an incorporation of coefficient like the present value discount rate which is related to the uncertainty of the estimated values.

In determining the value of income in close agreement with [REI p.166] we could say that economic income could be sorted into the three categories:

1. *Income derived from increases in revenues (output side see Fig.2) related to the subject intangible*
2. *Income derived from decreases in expenses related to the subject intangible*
3. *Income derived from decreases in investments related to the subject intangible.*

These three categories could be clearly identified in our Figure [Company in surrounding world].

INCOME METHOD IN THE CASE OF ASSET ASSEMBLAGE

Analyzed asset often is a part of asset assemblage, and it is necessary to distinguish its impact on value of inputs and outputs from the impact of other assets. Usable methods seems to be based on the following types of income

1. Residual income is the total income generated by the economic unit that uses the subject intangible less a specific capital charge. The capital charge represents a fair economic return on the tangible and other intangible assets associated with the subject intangible asset
2. Profit split income is the total income generated by the economic unit that uses the subject intangible split between the subject intangible and all of the other tangible and intangible assets that are used by the economic unit. The split percentage should be a market-derived allocation percentage between intangible asset owners.

In principle the idea residual income analysis could be altered to a set of incremental income methods, which are based on changes in revenues and costs made by the inclusion of the asset under evaluation.

The difficulty with application of profit split uses the split coefficient, which is claimed to be mainly market given number. In our work we assume not existent marked for asset/like entities, and the determination of this coefficient represent a serious problem, which we will analyze late.

INCREMENTAL METHOD ILLUSTRATIVE EXAMPLE

As an example we give and example similar we found in REI book. Adjusted to fit our nonexistent asset market assumption and application of incremental method:

The objective of our appraisal example is to determine "use value" of technology (a kind of knowledge & information package). The technology intangible is named the GreatT and it is used to enhance capability of a standard production line. Products of the line are sold on the market (the second quadrant of Fig.8.) and the sale thanks to the application of GreatT technology generate 30 millions revenue. We assume the tax rate equals zero, and for our illustrative example risk-related present value discount rate to be also zero. The useful lifetime period is assumed to be three years, and operating expenses 80%. Cost of using other assets (the capital charge) for one year is 1milon euros.

Valuation of asset GreatT technology -residual revenue income method			
	Year 1	Year 2	Year 3
Projected revenue	30	30	30
- Operating and other expences	24	24	24
=Net income (predebt, zero tax rate)	6	6	6
-Capital charge on the associated assets	3.8	3.8	3.8
=Economic income	2.2	2.2	2.2
x present value discount factor (based on discount value discount rate 0%)	1.0	1.0	1.0
=Discounted economic income	2.2	2.2	2.2
Indicated value			**6.6**

Value of asset with GreatT technology –incremental economic income method			
	Year 1	Year 2	Year 3
Projected revenue with GreatT	30	30	30
Projected revenue Without GreatT	28	28	28
=Economic income increment	2	2	2
x present value	1.0	1.0	1.0

discount factor			
=Discounted economic income	2	2	2
Indicated value			**6**

The application of two incremental income methods gives us two different results. The difference is inherited in method assumptions. In the residual income methods we rather unrealistically assume that all our income from asset assembly comes from the GreatT technology. In reality the production line alone might generate nonzero income even without application of GreatT technology. The case of incremental economic income seems to be better estimate, on other side it uses two sets of projected revenues and therefore might be less prone to error.

Reducing uncertainty is the main purpose for all economic measurement methods. In our quest for quantification methods we found established practical methods for evaluation of intangible assets as the most suitable for the purpose of determining value of information. [REI99] gives the guidance between practical cases of evaluation methods.

The approaches mentioned below are used in determing value of information managerial decision making. In some sense, the method of determining value by interaction with the surounding in more abstract valuation of intangible assets.

9. BENEFITS PRODUCED BY JOIN ACTION OF TWO ASSETS

In order to determine value of a information or knowledge-like asset we need to observe measurable value realization process. The process might be like the production of goods, which are consequently sold on the free market. Unfortunately, the information or knowledge-like asset usually needs another asset to produce output of measurable value. The second asset is often tangible or a set of tangible and intangible assets.

In the following we would discuss the way, how to determine value of an asset if the asset can realize its value only as a part of the asset assembly. We believed that similar question has already appeared many times in economic and managerial sciences, and their methods and approaches could be extended also for our task.

At the beginning we have declared that the primary purpose of our valuation is to address the investment approving process like CBA analysis or the evaluation of the research project by the PART tool. The question, which part of the output value should assigned the particular asset seems too difficult too difficult to answer in general. Fortunately, the prime purpose of our article, mentioned above, enable us to narrow scope of conditions and situations we are interested in.

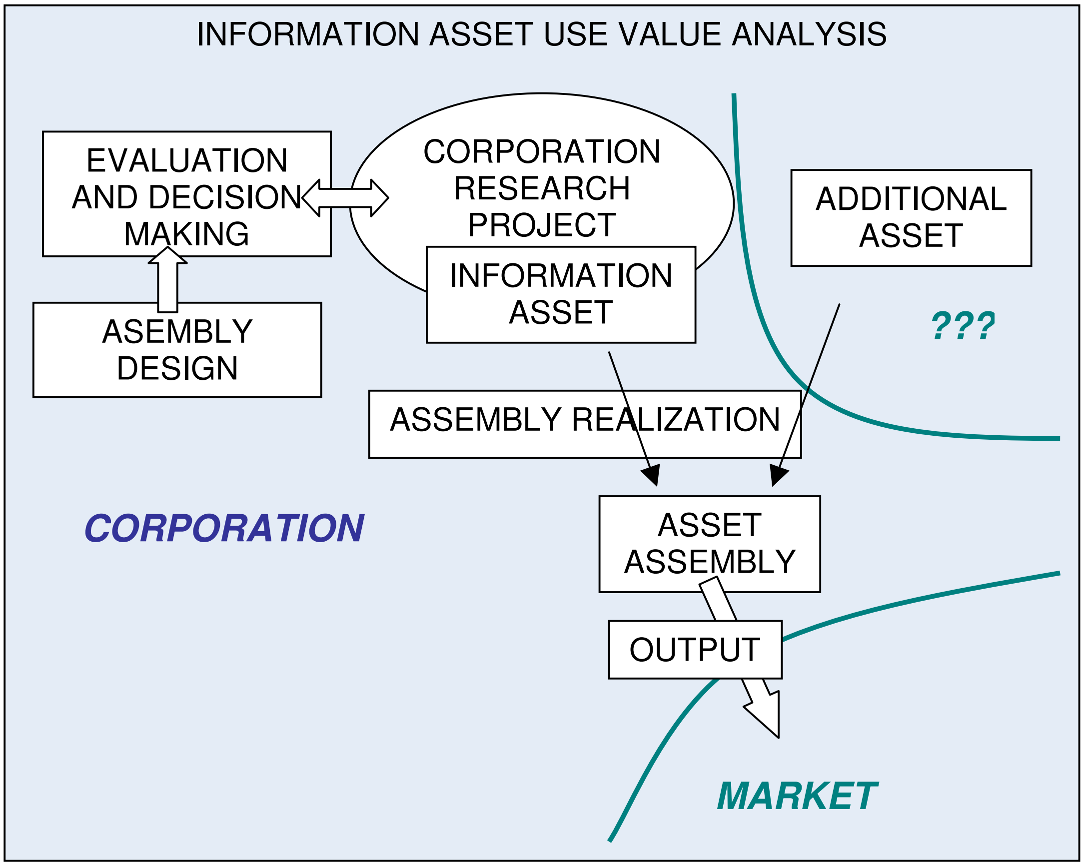
Value assessments are supposed to be a part of an investment decision or investment reporting processes. Basic framework is the decision whether the value of direct or indirect impacts exceeds project cost within reasonable uncertainty range. We assume that the investor asset value could be determined from the projected output value, which results from the information or knowledge-like asset use. At the beginning we would investigate relatively well-investigated case when the decision making is made within a large corporation.

INFORMATION ASSET USE VALUE

In order to simplify the task further we limit ourselves to investigate the value delivered via output of a particular asset assembly. For the user associated use value provides the upper limit at which the financing research project make a sense. We might expect, that the potential user may pay much smaller price.

In order to determine the value with the most accurate precision we need to decide, whether we are willing to assign the value to the design and process of asset assemblage or we consider it negligible. In some situation the act of asset assemblage process might be obvious and its cost negligible. In other situations the assemblage design and assemblage process itself might be unique and represent the main element producing the value of asset assemblage.

On the following figure we depict the process of the company decision process. We suppose, that information asset will be applied only once within an asset assembly with another asset. We suppose, that we can measure output value generated by joint action of assets. What is the asset use value?



The use value is usually derived from the difference between cumulative costs and cumulative revenues, as depicted in previous chapters.

The cumulative value of output generated by the asset assembly depends on market strategy of a company. Company might intend to keep its market share and the prices and intends just to increase profit through the lowered costs. Information asset value would be related the difference between value of output minus appropriate fixed and variable costs. If we neglect the cost of all supplementary phases we might consider that in our imaginative case the entire revenue from the market has been delivered by two component asset assembly.

For the further examination we need to specify the environment where the additional asset comes form. If the additional asset is freely available on the market we it can enter our consideration as an additional fixed cost. In this case in our decision process the information or knowledge-like asset should be assigned by entire surplus value generated by the asset assemblage. This corresponds to the value determined by the intangible asset accounting technique named the income method

If the second asset is produced in parallel within similar research or technological project in the company the surplus revenue of entire investment should not be assigned exclusively to the information or knowledge like asset. The surplus value of the assembly output should be assigned proportionally between these two assets by the transfer pricing method, which we discussed before. The cost of both projects should not exceed the expected output value.

As a third case we consider the case, when the second asset is not available at present and will be produced by some way in future and cost is reliably not known. This probably presents a limit of decisions process based on analysis and in certain sense present limit of our article. The decisions are probably made quite frequently, but they are not based on strictly careful assessment of profits and revenues. They might be quite rational, especially if the spared capacity or material would be wasted anyway and other options are not available.

FROM THE CORPORATION REVENUE TO THE SOCIETAL BENEFITS

In the following we try to extend our thoughts from a single corporation to the entire society. The knowledge/information is then produced by the publicly financed research organizations, results are made available to entire society. Knowledge are implemented to the increase production or other efficiency, and the profit passed to the entire society. Societal surplus is a key concept of the cost-benefit analysis.

The cost benefit analysis provide us with the guidance, how benefits should be determined. Effect of the projects should be separated to two classes: direct real or technical effects and the pecuniary effects. The basic difference between them is that first type is characterized by the provable direct benefits at least to the producer. The pecuniary effects are those effects which are associated with additional redistributory effects.

Market balance is assumed when demand curve intersects supply curve.
Basic scheme of the benefit calculation relies on the form of the demand curve and lowering cost in the supply curve. The benefit could be divaded to two parts. First of the benefit goes directly to the product users in the form of lower price. The second part of benefits go to the users attracted by the lowered cost. One should note, that extension of the user base, is principially different from extension of market share. Extension of market share occurs usually at expense of other producers, a the effect is associated with strong redistributory effects.

How the corporate methods differs from benefit methods.

As the first the information enters the market and is used primarily by commercial entities. The simplest example might be, that producer of the information has a monopolistic position and has full information about the way how information is used. The fully informed monopolist set the price at such which almost fully represents the benefits of his corporate customers (diminished by the cost of learning, adaptation etc.) In that case the monopolistic

VOI =SUM(additional benefits of all producers– learning, verification, propagation and adaptation cost) x time period

This is the simplest model of societal VOI and seems to correspond perception like Earthquaqe VOI. Formula above aqutally represents integration of benefits over certain time period. Strongly resembles estimation which could be earnred by enterpreur in assumed monopoilistic position.

Analogy with the enterpreuer's evaluation of the market might go further. In the case, that at least one producer exists, value of investment is the value above lowered by a certain value.

10. VALUE OF THE CAPACITY AND SKILL RESERVOARS

PRESENCE AND VALUATION OF MARKET ABSORBED INFORMATION…
PASSING THE KNOWLEDGE FROM ENTERPREUER TO LIBRARY

In our society there is a plenty of information, embeded in technologies, patents, books and functioning instruments. Their origin is often not know and it is a question of technology historitians or a matter of national prestige. In spite that development of the information is associated with often heroic effort, at the present those knowledge/ideas are available at the cost of library storage, and the economy of their use is determined primary by the cost of information adaptation and learning.

In our work we often supposed validity of an assumption that the knowledge development process could be, at least in principle, encircled into the form of some entity, which could be separated from the rest of the society. This is not necessary true, and this approach is ~~named as commodity-like and~~ criticized by [Boz02]. Author in the case of internet development gives a proof, that the internet invention was not an single act of single researcher or team of researchers but much more complex interplay of many research projects and research teams over extended period of time. Author proposes his own model- churn model of evaluation of scientific outputs.

~~Another criticism of this, in this case, impact localizated within time period is mentioned in [CLA06]. They mentioned, that in fact most of the board participants agreed, that~~

~~research center acts more like an provider of continual decisional support processes. In this case as well as before, we could not see the output of research institute as a sum of evaluated outputs.~~

~~Humans always value the present cost with the future possible benefits. Even cares about the benefits which exceeds duration of their entire life. There seems to be a rational behavior to build an capacity to act against Impact of highly improbable - * This was brought to the attention by XYZ Poznan.~~

11. CONLCUSIONS

~~Based on previous work we tried to introduce present believes about the position of research and scientific work in overall society. This paper intended to introduce intangible assets accounting concepts into the ordinary scientific decision making process.~~

~~This is to introduce concept of valuation of the work the relation of the scientific and research work of his work for the entire society.~~

~~This paper tackles rapidly developing fields like measurement of intangible assets, decision theory, and urgent need of application of economic views in scientific project decision making.~~

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LITERATURE

[BER99] Giampiero E. G. Beroggi: *Decision Modeling in Policy Management*, Kluwer Academic Publishers, Boston, 1999.
[BOZ02] Research Policy, Elsevier, Vol. 31 (2002) p.769-794
[CLA06] W.Clark, L. Holiday: *Linking Knowledge with Action for Sustainable Development*, The National Academic Press, Washington, 2006.
[CLE96] Robert. T. Clemen: Making Hard Decisions, Duxbury Press, New York, 1996.
[DAF86] Richard L. Daft: *Organization Theory and Design*, West Publishing Company, 1986, New York.
[DAL05] Kimiz Dalkir: *Knowledge management in theory and Practice*, Elsevier, 2005 New York.
[EPA08] Evaluating Research Efficiency in the U.S. Environmental Protection Agency, National Academic Press, Washington, 2008.
[GPR93] (08.10.2008) **http://www.whitehouse.gov/omb/mgmt-gpra/gplaw2m.html**

[HUB03] Douglas Hubbard: Applied Information Economics (AIE) Analysis Of the Desktop Replacement Policy for EPA, 2003.
[HUB07] Douglas W. Hubbard: How to Measure Anything- Finding the value of Intangibles in Business, John Wiley, Hoboken, 2007.
http://www.federalelectronicschallenge.net/resources/docs/aie_desktop.pdf
[KIR02] Craig. W. Kirkwood: Decision Tree Primer, 2002.
http://www.public.asu.edu/~kirkwood/DAStuff/decisiontrees/
[KRA99] Lee J. Krajewski, Larry P. Ritzman: Operations Management-Strategy and Analysis. Addison Wesley, 1999, Reading, Massachusetts.
[LEH08] Mark. L. Lehto, James R. Buck: Introduction to human factor and ergonomics for engineers, LEA, New York, 2008.
[NAS96] Tevfik F. Nas: Cost-Benefit Analysis, Sage, Thousend Oaks, 1996.
[NRC07] National Research Council: Framework for the review of Research Programs of the National Institute for Occupational Safety And Health, National Research Council, 2007.
[SAM88] D. Samson: Managerial Decison Analysis, IRWIN, Illinois, 1988.
[TER07] Milan Terek: Analýza rozhodovania, Iura Edition, 2007.
[TRANS] http://en.wikipedia.org/wiki/Transfer_pricing

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Identifying challenges in the provision of GEOSS. An evaluation based on game theoretic and economic concepts

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Identifying challenges in the provision of GEOSS.
An evaluation based on game theoretic and economic concepts.[1]

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Abstract – Growing environmental concern has fueled the discussion about the establishment of an international institutional arrangement for cooperation on Earth observation. The Global Earth Observation System of Systems (GEOSS) comes as a timely solution, bundling data, technologies and existing observation systems, and providing crucial information about the state of our Earth. However, the implementation of GEOSS faces challenges, and some of them are related to the fact that contribution to GEOSS is voluntary. Additionally benefits of GEOSS are enjoyed by contributors and non-contributors alike, such that GEOSS can be classified as a public good, whose provision is usually corrupted by "free-riding". This paper identifies challenges in managing and implementing GEOSS as a public good. To figure out scenarios, which can possibly arise, and find resolutions for them we examine how these problems are discussed in economic and game theoretical literature. We further examine problems concerning the user integration of GEOSS, and the interaction between Earth observation science and policy.

Keywords: GEOSS, collective action, game theory, user integration, science-policy-interface,

1. INTRODUCTION

In recent years, global environmental challenges have created a pressing need for increasing investment in remote sensing spacecraft to obtain data about the environment and natural resources and subsequently for international institutional arrangements for the cooperation on Earth observation and space applications. In 2003, the first political summit on Earth Observation was convened in Washington D.C., where the need to strengthen "cooperation and coordination among global observing systems and research programs for integrated global observation" (Declaration of the Earth Observation Summit, 2003) has been proclaimed. Only when tight collaboration among providers and operators of satellite systems is achieved, duplication of effort can be diminished or avoided, and space acquired data can be obtained in an efficient and cost effective way (Bailey, Lauer and Carneggie, 2001).

As a consequence the Global Earth Observation System of Systems (GEOSS) has been launched in 2005 to bundle data, technologies, existing and future observation systems and forecasting models, in order to collect purposeful, high resolution Earth observation data, aiming to add value to Earth observation systems and activities through coordination (www.earthobservations.org). In doing so, GEOSS does not intend to be only technology- or curiosity-driven, oriented towards basic scientific research and exploration of new projects; but there was consensus in the Group on Earth Observation (GEO) to focus in particular the societal benefits which can be derived from Earth observation programs (Christian, 2005).

[1] This study resulted of our engagement in the FP6 project Global Earth Observation- Benefit Estimation, Now, Next and Emerging (GEO-BENE) funded by the European Commission. For more information, please visit: www.geo-bene.org

GEOSS is coordinated and administered by GEO. The GEO has established a ten-year implementation plan for the period 2005-2015 which outlines the vision, purpose and expected benefits of GEOSS and provides a framework for cooperation and interaction within which nation states and organizations can develop new project and coordinate their strategies and investments. The expected benefits of GEOSS are categorized in nine societal benefit areas (SBAs): disaster, health, energy, climate, water, ecosystems, agriculture and biodiversity. To guide the implementation of GEOSS four Committees and one Working Group (Working Group on Tsunami Activities) have been established. The committees are organized around four cross-cutting areas of user interface, architecture and data, science and technology, and capacity building. A range of working groups referred to as tasks, which consist of several GEO members or participating organizations, are assigned to the Committees and the SBAs. Tasks are meant to develop and provide the components (monitoring systems, models, data,…) of GEOSS, and are administered by interested GEO members or participating organizations. Under the Work Plan 2007-2009 73 tasks were approved which were merged into 42 strategic, overarching tasks under the Work Plan 2009-2011 (cp. Work Plan Management Information document, 2009). As of July 2009, GEO's Members include 79 governments and the European Commission and 56 intergovernmental, international, and regional participating organizations (www.earthobservations.org).
The objective of the 2003 summit, to foster collaboration on Earth observation, was not new and has been expressed in other charters of existing international cooperative programs on remote sensing; for instance, under CEOS (Committee on Earth Observing Satellites) which has been established in 1984 and is now part of GEO. The 2003 summit, however, has revised the goals and returned them to the spotlight of international attention and political approval (Macauley, 2005).

Cooperation in GEOSS faces challenges: Earth observation has a history of restriction due to matters of national security and sovereignty; many countries lack consistent political and fiscal support to engage in cooperative space projects; or there exist incompatible data access and pricing policy among satellite programs and types (Thomas, Lester and Sadeh, 1995). Also the question of funding and financial commitments towards GEOSS, which is necessary to ensure long-lasting collaborative efforts, remains important (Macauley, 2005). Additionally, GEOSS is a "system of systems" and the challenges concerning the technical compatibility of the systems and the establishment of technological standards can occur.
Another aspect, which can hamper cooperation concerning GEOSS, and which is the starting point of our paper, is the similarity of GEOSS with a public good. Public goods are characterized by non-rivalry, - an agent's consumption does not happen at the expense of another agent's consumption; and non-excludability,- no agent can be excluded from consuming the good. This implies that the contributors to a public good are not adequately remunerated for their contribution, and contributors and non-contributors equally benefit from the public good. Consequently, agents do not have sufficient incentives to provide the good and often decide to free-ride. This leads to an underproduction of the public good.
GEOSS can be understood as public good in two ways: (i) Participation in GEOSS is voluntary and shall be made accessible freely or at a very low cost. Hence, no one can be excluded from

using it. (ii) On the basis of Earth observation data, policies and decisions on the environment and natural resources, - or according to Smith and Doldirina (2008) decisions in the name of the public interest, are realized. When GEOSS is used to improve the state of the environment, no one can be excluded from the accrued environmental benefits.

Keeping these assumptions in mind following considerations are explored in this study and embedded in economic and game theoretical concepts in order to figure out possible trends and scenarios (section 2):

- If contributions to GEOSS are voluntary, what are the consequences for the provision of GEOSS?
- What could be the implications of insufficient communication and information exchange between GEOSS participants? What is suggested in the literature to overcome this problem and what should be considered when doing so?
- How can technological/data standards emerge in a self-organizing process and in the absence of a binding data sharing agreement?
- What are the concerns when integrating of private providers to GEOSS?

Section 3 briefly touches on the impact and outreach of GEOSS concerning the integration of users and the establishment of an interface between science, technology, policy and users to guarantee a sustainable use of GEOSS.

2. CHALLENGES IN THE PROVISION OF GEOSS

2.1. Voluntary participation to provide a public good

The concept of collective action has a long history in several academic fields. Already in 1965 Olson challenged the prevailing consensus that groups automatically further their members' wellbeing and instead highlighted the pitfalls of collective action. Depicted in a simplified fashion, the GEOSS process is exemplary for the difficult provision of a public good: Contribution to GEOSS is non-binding and failure to fulfill one's commitment remains without consequences. The GEOSS tasks, which provide the GEOSS' components, are self-organizing and self- financing units. In achieving their goals, the GEO secretariat plays a facilitating and mediating role but does not offer financial support for the achievement of the tasks' goals. Consequently the question emerges how committed contribution to GEOSS can be ensured and how free-riding can be prevented. To analyze the contribution to GEOSS within a game theoretical framework three scenarios can be distinguished: (i) The tasks organize themselves, there is no supervising or coordinating institution, (ii) there exists an external institution which coordinates the process but has no enforcement or sanctioning powers, (iii) there exists an external coordinating institution with enforcement and sanctioning powers which tries to implement a binding contract.

(i) A broadly used example for the provision of public goods in environmental economics is the establishment of an International Environmental Agreement (IEA). Similar to GEOSS, no country can be forced to sign an IEA, and if it does, can withdraw from the agreement at any time. Consequently, self-enforcing agreements have to be established, which are mutually beneficial, and where no member of an IEA wants to withdraw and no non-member wants to accede. Barrett (1994) concludes that under certain functional specifications a self-enforcing agreement can only sustain two or three members. This result is supported by D'Aspremont et al. (1983) who conclude that the fraction of members to an IEA decreases with the number of countries affected by the environmental problem; because given a large number of affected countries, each country views its own contribution as negligible and decides to not contribute. Barrett (1994) adds that a tradeoff between the breadth and depths of an agreement exists: There is a high degree of cooperation when the net benefits between full cooperative and non-cooperative outcome are small. The larger the potential gains to cooperation, the greater are the benefits of free-riding, the larger incentives to defect and hence the smaller the number of signatories. Barrett infers that international treaties cannot induce great changes compared to the business-as-usual situation, but tend to codify actions which nations were already undertaking.

The result that participation to an agreement with positive externalities is low, is supported by Poyago-Theotoky (1995) who focuses on the establishment of a R&D consortium. The analysis depicts R&D conducted within the consortium as a club good, which is non-rival but exclusive, and accounts for the exclusivity of research findings by assuming various levels of spillover rates: The spill-over rate to non-members is small and they do not profit to the same extent from the research findings as members of the research consortium. Only members of the research consortium enjoy full spillovers and have a comparative advantage to and a higher payoff than the non-members. Therefore they have an incentive to keep the consortium small. However, also in the case of a club good, a societal optimum can only be achieved when all agents participate in the provision of the good. All in all, these findings imply that the socially optimal size of participation to an agreement on the provision of a public good is full cooperation, but that self-organized cooperation will always be smaller than the optimal size.

(ii) Can the above obtained result be altered when an external coordinating institution is installed? An external institution with little or no enforcement power could help to strategically frame a situation in such a way that cooperation is mutually desirable, e.g. by revealing situations where most benefits can be achieved; by influencing the issues which are negotiated; by modifying the accession and abrogation rules (cp. Yi, 2000; Yi, 2003; Finus and Rundshagen, 2003; Carraro and Marchiori, 2003), by linking negotiations (Carraro and Siniscalco, 1995; Carraro and Marchiori, 2003), or providing side payments to induce non-contributors (Carraro and Siniscalco, 1995). An external institution can also propose the establishment of multiple agreements at a time, i.e. various agreements according to the specific interests or financial endowments of agents. Instead of aiming to achieve one agreement with full cooperation, several smaller agreements can be established at a time. By assumption, smaller agreements are less effective than larger agreements or a full membership agreement. This gap in effectiveness can be compensated by engaging more agents in several smaller IEAs, than when only one agreement is offered which attracts few agents (cp. Yi, 2000; Yi, 2003; Finus and Rundshagen, 2003; Carraro and Marchiori, 2003).

An external institution needs full information on the agents, and their benefits and costs to guide the process of cooperation effectively. But usually information are asymmetrically distributed which poses problems when trying to alter a situation strategically,- in particular for an institution which tries to impose a binding contract for the members.

(iii) What can be expected of an external institution with enforcement or sanctioning powers, aiming to establish a binding agreement? Usually an optimal contract specifies what each agent has to do in every situation and arranges the distribution of realised costs and benefits in each event.

When information is asymmetrically distributed two situations, leading to the establishment of a suboptimal contract can emerge: adverse selection, - each member's ability is known only to himself, when a contract is set up they do not reveal all necessary information; or moral hazard, - which describes post-contractual, self-interested misbehaviour in situations when effort is not observable. This can lead to the well known hold-up problem, which refers to a situation where large, specific investments occur, which make the asset owner very vulnerable to opportunistic behaviour. Without adequate protection specified in a contract, the agents simply refrain from investing.

Suboptimal contracts which cannot specify all arising circumstances can lead to renegotiations. Ex-post renegotiation can be advantageous when in the course of contract implementation more information is revealed, but the knowledge of possible renegotiation impedes the contract to be drafted in an effective way in the first place. To reach a contract a principal or external observing institution can set incentives like penalties or bonuses, establish compensation rules, adjust remuneration systems to observed output (if it can be observed) or allocate rewards by comparing agents' performances (Milgrom and Roberts, 1992).

Summarizing, an external coordinating institution is crucial to successfully achieve the goals of cooperation. The self-reliant establishment of mutually profitable contracts has not proven effective in sustaining cooperation among a large number of agents. On the other extreme, an external institution trying to establish a binding agreement could fail in doing so because it lacks information about the agents to design an effective agreement. To guarantee the acceptance and efficiency of an external coordinating institution it is necessary that members define clearly what they expect of the coordinator and by guaranteeing a bottom-up legitimization process.

2.2. Informational constraints

In the past, unawareness among the tasks about each others' research goals or progress has been observed. But this information is necessary to work together efficiently and to strengthen the cross cutting and transverse dimension of GEOSS across SBAs, models and system types, and Committees (cp. Annex I to Work Plan 2009-2011 V1, 2008). Also the exchange of information between the secretariat and the tasks is crucial. Currently, the only reporting mechanism between the secretariat and the tasks are the task-sheets, which are updated every 4 months, and include a description of the goals, work to be done and progress.[2] Are the task-sheets sufficient as reporting mechanisms from the tasks to the GEO secretariat? This leads to a suggestive distinction: are the channels of communication insufficiently established; or are there strategic incentives to provide only insufficient information? The economic literature on information

[2] AVAILABLE ON FTP://FTP.WMO.INT/PROJECTS/GEO/TASKSHEETS/2008-01/; 15/07/09

disclosure is offering an understanding for agents' incentives to (not) reveal information voluntarily. In what follows we examine the consequences of insufficient communication and lacking information and the possibilities to overcome the problem.

Not knowing the characteristics of the fellow agents refers to a situation of asymmetrically distributed information. A valuable investigation about the consequences of adverse selection (cp previous subsection) has been conducted by Akerlof (1970), who depicts the collapse of a market as consequence of informational asymmetries: buyers lack information about the state of the assets offered in the market; high quality assets and assets of lower quality sell at the same price. Low quality assets bring down the average price and drive the high quality assets out of the market. This implies that lacking information when cooperating to achieve GEOSS can lead to lower than possible outcome. Lacking information can be reflected by the engagement of organisations or individuals at high level positions who do not know sufficiently about the GEO process or are constraint by time to satisfactorily perform their duty. The consequences can range from poor leadership and therefore a lower than possible outcome, or a tarnished reputation of the entire GEOSS process and lower incentives for participants to actively contribute to the process.

Milgrom and Roberts (1992) introduce two mechanisms to correct cases of adverse selection: (i) Signalling refers to a situation where an agent adopts a specific behaviour that, when properly interpreted, reveals his 'true type', e.g. that he is highly productive. This behaviour is usually too costly to adopt for agents which are e.g. of lower productivity. This is referred to as "self selection constraint". (ii) Screening refers to an activity undertaken by the agents without sufficient information about the types of the fellow agents, in order to separate different types of those privately informed agents along specific dimensions. This is often done by offering a variety of alternatives each intended for one of the various types of informed parties, whose choice then reveals their private information. Overgaard (1991) adds that by repeated interaction low quality assets or characteristics are weeded out of the market. All in all this demands incentive setting which an organisation like the GEO secretariat could arrange. That the presence of external, monitoring institutions can have a positive effect on information disclosure is pointed out by Ayra and Mittendorf (2005), who analyse the effect of simultaneous information disclosure on competitors and on third parties: when private information is only revealed to competitors they run risk that it will be used strategically against them, whereas when third parties are present this is not likely to occur.

Again, this analysis calls for an external party to monitor and foster communication.

However, these results imply that, when investigating how communication can be improved, the presence of strategic considerations and disincentives to engage in communication should not be neglected in favour of mere technical aspects, like drafting more sophisticated task sheets or convening more meetings.

2.3. Standards setting and the role of a technological leader

GEOSS is a 'system of systems' where technical standardization and interoperability of the components has to be ensured. It is broadly acknowledged that the GEO secretariat plays a facilitating role to achieve that. This section focuses on the questions how standards can emerge in a self-organizing process and in the absence of a binding data sharing agreement.

Interoperability and data compatibility clearly yields increased benefits in the form of network effects, for all participants. It can be distinguished between direct network effects, e.g. improvement of quality when an additional household is added to a telecommunication network; and indirect effects, e.g. when a complementary good, like software, become lower in price as the number of users of the good, a computer, increases. Similar to the provision of a public good, benefit can increase when the size of the network increases (Liebowitz and Margolis, 1994).
However, there are reasons for not being the first to engage in the creation of a standard or network. Bliss and Nalebuff (1984) or Melissas (2005) show how agents delay the private provision of a public good, or adoption of a new, socially valuable technology, or the entering of a market, hoping that others will undertake these steps first, knowing that pioneering entry results in immediate losses to the entrant until other agents join the network. Alexander-Cook Alexander-Cook, Bernhardt and Roberts (1998) have added that the second entrant acts as a signal revealing to other agents that the network is believed to be profitable. But the knowledge that another agent might undertake this step reduces the incentive to do it first. As a result, a more informed group of agents may reach a worse outcome.
In this context, Choi (1997) analyses a game where agents are subject to an irreversible technology choice with network externalities. The value of the technology will only be known to the fellow agents when a user has tried it. Even if they find out that the declined technology is better, they pick the technology which has been chosen by the previous agents; because herd behaviour is driven by the fear of being stranded and locked in with a technology, or standard, which no one else uses. This implies that this data standard must not be the 'best' or most broadly approved, but that it can simply result from a, maybe arbitrary, choice of one agent. However, this result is put into perspective by e.g. Vergari (2005) who argues that empirics find little support for Choi's result concerning the situation when being stuck with an inferior standards, and investigates how the environment affects herding behaviour; or Witt (1997) who asserts that lock-in into an inferior technology needs government intervention, and that new technologies can always enter a market successfully as long as a critical threshold has been passed.
These concepts suggest that the first-mover bears additional costs and therefore refrains from exerting effort. Hence, standard setting in GEOSS could encounter difficulties or be delayed; or be not based on a compromise that satisfies all participants, but rather on the pertinence of a first mover who emerges as technological leader.

2.4. Public-Private-Partnerships in GEOSS

Even though a formalized relationship between the private sector and GEOSS still has to be developed, the commercial sector will play an important role in the future of GEOSS. Currently, tasks include private contributors only sporadically and they have to be approved by the member governments and by the GEO secretariat.[3] For instance, collaboration has been decided between GEO and IRIDIUM® Satellite LLC (cp. Press release from 31.01.08, www. http://www.earthobservations.org/pr_pr.shtml, July 2009). Macauley (2005) summarizes that

[3] Personal communication in May 2008

commercial providers could help making the data applicable for the real world, but could also cause difficulties when data and pricing policies for GEOSS are formulated.
In these regards, many questions emerge: how are private initiatives perceived by the GEOSS members? If private firms are allowed to contribute directly to GEOSS, what are the implications on the openness of standards, reuse and accessibility of data, costless licensing and public good nature of GEOSS? Even though private contributions to GEOSS are labelled as voluntary, could this be credible or could discredit GEOSS?

The economic literature neither provides answers to these questions nor a unique framework for Public-Private-Partnerships (PPP), but there are some points which should be kept in mind. Besely and Ghatak (1999) affirm that providing a public good raises the possibility for partnerships to exploit the comparative advantage in production and relative project valuation of different parties. Levinson et al. (2006) point out, that the private sector is usually motivated by profits and might therefore give insufficient weight to quality or safety for the general public. Both partners will have risks involved in the partnership. It has been asserted that PPPs work best if the roles and responsibilities for each partner are clearly defined. Usually the public agents are responsible for defining the details, the objectives, that standards are met and enforced regarding the public's wellbeing and safety. The private initiatives take the risks in new approaches or designs that the public agent is not always able to achieve. The long term profits depend to a great part on how the private agents can handle the risk transferred to them and how the public agents manage the contracts.

3. CHALLENGES IN THE USER ENGAGEMEBNT OF GEOSS

In this section three aspects of user integration in GEOSS are briefly discussed: (i) integration of users in the process of GEOSS, (ii) promoting GEOSS and making GEOSS more visible in the general public, (iii) establishing an interface between Earth observation science and users/ policy makers.
(i) GEOSS has decided on a benefit-driven approach, such that the integration of users is crucial and subject to frequent discussion. However, still under the Work Plan 2007-2009 the performance of most tasks focussing on the integration of users has been rated as deficient (2007-2009 Work Plan Progress report, 2007). The main focus of issues on user integration should not only rest on how the end-users can access GEOSS, but also on how they can be integrated in the process of designing and implementing GEOSS. The integration of users in an earlier stage, in the stage of shaping GEOSS, could counteract a tendency that we have called a "Known-user-Bias": Within the process the needs of future users are not sufficiently anticipated. Usually, user evaluations focus on traditional user groups and customers which are already known and thereby e.g. exclude user groups in countries which currently don't belong to the main participants of GEOSS. If GEOSS should have long-lasting future prospects, and a sustainable utilization of GEOSS shall be guaranteed, a broader user community has to be anticipated. This refers also to the integration of developing countries, which could take the role as main users of GEOSS, but currently do not contribute significantly to GEOSS.

These considerations advance the question how GEOSS shall look like in the future. Will the contribution rest with established organisations and member states or shall even a broader range of people be engaged, such that GEOSS takes the shape of a social network which includes public maps or local information?

(ii) In these regards, questions about how GEOSS can become more visible for the general public and also for various institutions engaged in environmental or developmental issues have emerged. To raise political value and credibility of GEOSS, the establishment of Performance Monitoring and Evaluation indicators has been suggested to measure and assess the outcomes and impacts of GEOSS, to make the processes of GEOSS more transparent and facilitate communication among GEOSS components, and to make GEOSS more visible to the broader public and facilitate communication to the (potential) users of GEOSS. To communicate the usefulness and necessity of GEOSS for the everyday life to the broader public, could also help GEOSS to raise funds for its future sustenance (GEOSS Performance Monitoring & Evaluation Framework, 2008).

(iii) The final users and decision makers can access GEOSS via the GEO web portal.[4] However, the users are facing a variety of components, data and information on the web portal, such that the question arises whether a web portal, as only interface between science and users, is sufficient. After all, users shall not be limited to high level, national research institutions, who have the means to handle these complex data sets easily, but GEOSS shall address and serve users at varying scales to increase their benefits in the respective SBA. In these regards there exists a GEO capacity building initiatives, which exerts considerable efforts to coordinate existing Capacity building initiatives, in order to strengthen human, institutional and infrastructural capacity in Earth observation, in particular in developing countries, which is central to the achievements of GEOSSs' over all goals and benefits (GEO Capacity Building Strategy, 2006).

The question remains how the interface between Earth science and policymaking can be shaped. How can these information influence decision making? The dialog between scientists and policy makers has often been evaluated as deficient, arguing that natural sciences do not sufficiently set their scientific and technical findings into policy relevant contexts. Consequently, the mere provision of data, information and models on a web portal might not be sufficient to integrate the information into decision making (cp. Watson, 2005; Maasen and Weingart, 2005). Usually a monetary quantification and estimation of benefits and costs regarding the consequences of certain politics has proven its worth as tool of communication from science to politics (cp. Dybas, 2006; van den Hove, 2007 or Watson, 2005).

At this point the EC sponsored project Global Earth Observation Benefit Estimation: Now, Next and Emerging (GEO-BENE)[5] could play a significant role. GEO-BENE's objective is to develop methodologies and analytical tools to assess, - qualitatively and quantitatively, benefits in all nine SBAs, and to draw conclusions from the modeling exercise for supporting the implementation of varying policies and decisions. Even though the project terminates in June 2009, it could serve as a prototype for follow-up projects, which aim at setting the value of the Earth observation data into a politically and socially relevant perspective.

[4] The GEO portal can be tested and evaluated on http://www.earthobservations.org/gci_gp.shtml, where more information is available; 16/07/09

[5] www.geo-bene.eu; 16/07/09

However, the economic rational propagated by GEO-BENE might not be sufficient to inform about the needs of user communities on the regional or local scale or particular environmental services, which cannot be quantified easily, but whose information is crucial for sustainable policy making. Therefore, more social scientists, - sociologists, political scientists, anthropologists, could be introduced into the design and implementation process of GEOSS, to enhance the understanding and integration of the user into GEOSS and guarantee its sustainable and long lasting use.

4. CONCLUSION

The research questions discussed in this study and the applied game theoretical and economic concepts are not exhaustive, but some recurring tendencies can be identified. Due to its non-exclusivity and non rivalry GEOSS has been identified as a public good, whose provision is often difficult to achieve by a group of self-organizing agents. Also the tasks which develop and provide the components of GEOSS are self-organizing and self-financing such that the GEOSS process could be prone to problems. In these regards, literature reveals that the number of participants to an agreement which arranges the provision of a public good is decreasing with an increasing number of beneficiaries; or that a trade-off between the number of contributors and the effectiveness of a public-good agreement can exist. Therefore, it is suggested that most processes concerning the provision of a public good demand an external institution as supervisor or regulator, which sets incentives to achieve the particular goals and coordinate activities. The GEO secretariat fulfills this role by providing guidance for the GEOSS components, establishing a framework for cooperation and guaranteeing political approval for the process, but does not provide financial support to the tasks which could hamper commitment and involvement of the tasks towards GEOSS. To support its role, we propose a GEO coordination fund, which is sufficiently large to overcome the well known problems of international and cross-sectoral self organization.

Another problem which could emerge in coordination processes is the asymmetric distribution of information and deficient communication which can constitute a major barrier to the establishment of a mutually beneficial project like GEOSS. This can be attributed to either missing or deficient channels of communication, or lacking incentives to reveal information and engage in useful communication. Communication and reporting mechanism will become an important issue within the next Work Plan 2009-2011, which requires the GEO tasks to engage in close collaborations with each other across benefit areas. Therefore, comprehensive knowledge and information about each other and of the respective research and goals is of advantage. Literature suggests that an external monitoring institution can have positive effects in this regard.

Finally the question has been investigated how technological and data standards can emerge in self-organizing processes without a binding agreement. Economic literature suggests that standard setting could be delayed, because first-movers bear additional costs and therefore delay action, or encounter problems, because suboptimal standards being embedded in a network of users can be favored over optimal standards without such a network. Intervention of an external monitoring institution could also help in these regards.

To accomplish a sustainable use of GEOSS, a timely integration of various user communities in the design, implementation and utilization of GEOSS is necessary. The envisioned gateway between science and users shall consist of an all accessible GEO web portal. But this might not be enough to convey the relevance and added value of Earth observation data to policy and decision makers. Instead, the integration of social scientists in the process of designing and implementing GEOSS, or a quantification of accrued benefits of Earth observation could constitute a valuable step to bridge the gap between Earth and space science and decision-makers.

Overall, GEO has put itself a nearly impossible target to build GEOSS to serve 9 SBAs. It will involve both international and cross-sectoral coordination. The latter gets barely implemented in sovereign nation states and for the former we have so far only one successful global example- the Montreal protocol on substances that deplete the ozone layer- and many failures. At the same time various environmental challenges become more and more persistent and the profile of international environmental negotiation processes is rising, and global Earth observations become a precondition for effective negotiations and efficient implementation. The cost of GEOSS is only one tenth of a percent fraction of the value at stake in the international environmental negotiations to overcome global environmental challenges. Thus, there is hope that the tremendous value of GEOSS will increasingly be recognized and the above stated problems will soon be overcome.

5. REFERENCES

Articles and Monographs:

Akerlof G. (1970). The Market for "Lemons": Quality Uncertainty and the Market Mechanism. The Quarterly Journal of Economics 84 (3), 488–500

Alexander-Cook K., Bernhardt D, and Roberts J. (1998). Riding free on the signals of others. Journal of Public Economics 67, 25–43

Arya, A. and Mittendorf, B. (2005). Using disclosure to influence herd behaviour. In Journal of Accounting and Economics 40, 231–246

Bailey, G. B., Lauer, D. T. and Carneggie, D.M. (2001). International collaboration: the cornerstone of satellite land remote sensing in the 21st century. Space Policy 17, 161–169

Barrett, S. (1994). Self-Enforcing International Environmental Agreements. Oxford Economic Papers, Special Issue on Environmental Economics, 46, 878–894

Besley, T. and Ghatak, M. (1999). Public-Private Partnerships for the Provision of Public Goods: Theory and an Application to NGOs. Development Economics discussion paper No. 17; London : London School of Economics and Political Science, Suntory and Toyota International Centres for Economics and Related Disciplines. http://publications.uvt.nl/eo/lse/t.besley/publications.html; 15/07/09

Bliss, C. and Nalebuff, B. (1984). Dragon-slaying and ballroom dancing: The private supply of a public good. Journal of Public Economics 25(1–2), 1–12

Carraro, C. and Marchiori, C. (2003). Stable coalitions. In: Carraro, C. (ed.). The Endogenous Formation of Economic Coalitions. Cheltenham: E. Elgare, 156–198.

Carraro, C. and Siniscalco, D. (1995). Policy coordination for sustainability: Committments, transfers and linked negotiations. In: Goldin, I. and Winters, L.A., (ed.). The Economic of Sustainable Development. Cambridge: Cambridge Univesity Press, 264–282.

Carraro, C., (ed.) (2003): The Endogenous Formation of Economic Coalitions. Cheltenham: E. Elgar

Christian, E. (2005). Planning for the Global Earth Observation System of Systems (GEOSS). Space Policy 2, 105–109

Choi (1997). Herd Behavior, the "Penguin Effect," and the Suppression of Informational Diffusion: An Analysis of Informational Externalities and Payoff Interdependency. The RAND Journal of Economics 28 (3), 407–425

D'Aspremont, C., Jaquemin, A., Gabszewicz, J. J. and Weyman, J. A. (1983). On the stability of collusive price leadership. Canadian Journal of Economics 16, 17–25.

Dybas, C.L. (2006). Biodiversity: The Interplay of Science, Valuation and Policy. BioScience 56, 10: 792-797.

Finus, M. and Rundshagen, B. (2003). Endogenous coalition formation in global pollution control: a partition function approach. In Carraro, C., ed.: The Endogenous Formation of Economic Coalitions. E. Elgar, Cheltenham, p.199–243.

Goldin, I. and Winters, L.A. (ed.) (1995): The Economic of Sustainable Development. Cambridge: Cambridge University Press

Levinson, D., Garcia, R. and Carlson, K. (2006). A Framework for Assessing Public Private Partnerships. In: Institutions and Regulatory Reform in Transportation (ed. Piet Rietveld and Roger Stough). Edward Elgar Publishers (in press), 284–307

Liebowitz, S. J. and Margolis, S. E. (1994): Network Externality: An Uncommon Tragedy. The Journal of Economic Perspectives 8 (2), 133–150.

Macauley, M. (2005). Is the vision of the Earth Observation Summit realizable? Space Policy 21, 29–39

Maasen, S. and Weingart, P. (2005). What's new in scientific advice to policy? Introductory essay. In: Maasen, S. and Weingart, P. (ed.) Democratization of expertise? : exploring novel forms of scientific advice in political decision-making. Dodrecht: Springer

Melissas, N. (2005). Herd behaviour as an incentive scheme. Economic Theory 26, 517–536

Milgrom, P.R and Roberts, J. (1992). Economics, organization and management. Englewood Cliffs, NJ: Prentice-Hall

Olson, M. (1965). The Logic of Collective Action : Public Goods and the Theory of Groups. Harvard University Press.

Overgaard, P. (1992). Product quality uncertainty. Strategic information transmission in product markets with adverse selection and adverse incentives. PhD Thesis. Université Catholique de Louvain

Poyago-Theotoky, J. (1995). Equilibrium and optimal size of research coalitions. Economics 43, No. 2: 209-226

Smith, L.J. and Doldirina, C. (2008) Remote sensing: A case for moving space data towards the public good. Space Policy 24, 22–32

Thomas, G. B., Lester, J.P. and Sadeh, W. (1995) International cooperation in remote sensing for global change research: political and economic considerations. Space Policy II (2) 131–141

Van den Hove, S. (2006). A rational for science-policy-interfaces. Futures 39, (7), 807-826

Vergari, C. (2005). Herd Behavior in Adoption of Network Technologies. Journal of Economics 86, (2), 161–182

Watson R. (2005). Turning science into policy: challenges and experiences from the science policy interface. In: Philos Trans R Soc Lond B Biol Sci, 2005 February 28; 360(1454): 471-477

Witt (1997). "Lock-in" vs. "critical masses" - industrial change under network externalities. International Journal of Industrial Organization 15, 753–773

Yi, S.-S. (2003). Endogenous formation of economic coalitions. A survey of the partition function approach. In: Carraro, C., (ed.). The Endogenous Formation of Economic Coalitions. Cheltenham: E. Elgar,80–127.

Yi, S.-S. and Shin, H. (2000). Endogenous formation of research coalition with spillovers. International Journal of Industrial Organization, 18: 229–56.

Documents:

2007-2009 Work Plan Progress report, November 2007; www.earthobservations.org/documents/work %20plan/work_plan_progress_report_2007_2009.pdf; last accessed in July 2009

Annex I to GEO 2009-2011 Work Plan (V1), July 2008; www.earthobservations.org/documents/work%20plan/geo_wp0911_v1_annex1.pdf; last accessed in July 2009

Declaration of the Earth Observation Summit; Washington, DC, July 31, 2003; http://www.earthobservations.org/docs/Declaration-final%207-31-03.pdf; last accessed in July 2009

GEO Capacity Building Strategy, 2006; http://www.earthobservations.org/documents/committees/cbc/capacity_building_strategy.pdf; last accessed in July 2009

GEO Work Plan 2009-2011, available on http://www.earthobservations.org/documents.shtml; last accessed in July 2009

GEOSS Performance Monitoring & Evaluation Framework, November 2008; http://www.earthobservations.org/documents/geo_v/11_GEOSS%20Performance %20Monitoring%20and%20Evaluation%20Framework.pdf; last accessed in July 2009

Press release "Idea of Flying Earth Climate Observation Sensors on Iridium NEXT Gains Universal Approval, Focus Moves to Funding" from 30/01/08; available on http://www.earthobservations.org/pr_pr.shtml; last accessed in July 2009

Work Plan Management Information document, January 2009 http://www.earthobservations.org/documents/work %20plan/geo_work_plan_management_090113.pdf; last accessed in July 2009

Online Information:

www.geo-bene.eu; last accessed in July 2009

GEO web Portal: http://www.earthobservations.org/gci_gp.shtml; last accessed in July 2009

Task Sheets: ftp://ftp.wmo.int/Projects/GEO/TaskSheets/2008-01/; last accessed in July 2009

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Designing Research Coalition in Promoting GEOSS. A brief overview of the literature

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Contents

Abstract The Global Earth Observation System of Systems (GEOSS) links a variety of existing and future observation systems and forecasting models into one comprehensive system of systems to provide accurate environmental data and to enable an encompassing vision and understanding of the Earth system. GEOSS is based on voluntary efforts, and shall be made accessible freely or at a very low cost, such that it bears properties of non-rivalry and non-excludability and can be compared with a public good. Agreements on the provision of a public good often suffer low participation. We apply a game theoretical approach to analyze GEOSS as a research coalition with varying spillover rates, in order to figure out whether a coalition with full participation can exist in equilibrium. We also focus on the question how varying spillover rates influence the size of the equilibrium coalition and suggest two measures, which can increase participation in equilibrium. The revision of the literature shows that the full participation is socially optimal and spillovers which take the form of strategic complements can lead to a high level of cooperation. Also measures like the linkage of negotiations and the formation of multiple coalitions can achieve a high level of participation.

Designing of research coalitions in promoting GEOSS. A brief overview of the literature[1]

Christine Heumesser[2]

1 Introduction

The Global Earth Observation System of Systems (GEOSS) is a very needed and timely effort to adress a range of global environmental challenges. Climate change, biodiversity loss, pollution, resource depletion, - to name a few, have become key factors, which influence many aspects and concerns of the public and human wellbeing. Under the auspice of the Secretariat of the Group on Earth Observations (GEO), GEOSS bundles sophisticated new technologies to collect a vast quantity of purposeful, high resolution Earth observation data, - an immense amount of data about air, water, and land measurements on various time and spatial scales from numerous land-based stations, floating buoys, and orbiting satellites, which ultimately shall be made available publicly or at low cost. GEOSS links a variety of existing and future observation systems and forecasting models, which are developed or provided by 42 task groups, into one comprehensive system of systems to provide accurate environmental data, to enhances the relevance of Earth observation for environmental problems, and to enable an encompassing vision and understanding of the Earth system, and supports policymakers, scientists and many other experts and decision-makers [cp.www.earthobservations.org].

The coordination and implementation of GEOSS lies in the responsibility of GEO, which was called into being after the 2002 World Summit on Sustainable Development and by the Group of Eight (G8). GEO has established a 10-year implementation plan for the Period 2005-2015, which outlines the vision, purpose and expected benefits of GEOSS. The benefits are categorized in nine societal benefits areas (SBA): disaster, health, energy,

[1]This discussion paper resulted from my engagement in the project 'Global earth observation - benefit estimation: now, next and emerging' (GEO-BENE) funded by the European Commission. http://www.geo-bene.eu

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climate, water, weather, ecosystems, agriculture and biodiversity, for which certain targets, like the improved understanding of climate variability, the water cycle, biodiversity loss etc. have been established. As of July 2009, GEO's Members include 79 Governments and the European Commission and 56 intergovernmental, international, and regional participating organizations [cp.www.earthobservations.org].In the course of the discussion paper they will be referred to as agents or countries.

Despite of the common aim to implement GEOSS and provide better information for better decision making, the public good character of these endeavours remains, such that the problems and challenges of GEOSS can be depicted as the cooperative efforts of a research and development (R&D) coalition. In games of R&D cooperation, firms undertake R&D investment to reduce their production cost and develope a strategic advantage over their competitors in the market. Thereby they produce information spillovers, which take the form of leaks, personnel movements, faulty patents [Yi and Shin (2000)], such that competitors benefit from research without paying. Depending on the extent of spillovers, the incentives to procure future investments are reduced; or put differently, give rise to the idea to form a R&D coalition as to internalize the positive spillovers. Members of a R&D coalition decide jointly on their investments taking each others' spillovers into account. This increases the country's profitability and the needless duplications of efforts can be avoided such that research investments and profits are expected to increase adverse to the non-cooperative situationHowever, spillovers to non-participants remain and strongly govern the size of the resulting research coalition, and ultimatly jeopardize the emergence of an industry wide, socially optimal coalition [Poyago-Theotoky (1995)].

GEOSS puts a similar problem on trial. The information and data compiled by individual efforts and investments enable the respective agent or country to implement policies and guidelines which are environmentally efficient, to generate forecasts, or to publish research results to heighten international prestige in a specific area. These information and data are excludable and therefore similar to club goods, but most of the implemented policies concern the utilization and conservation of the environment and natural resources, which are public goods.Benefits derived by the implementation of these policies can be described as private benefits, because the respective agent or country achieves cost advantages by implementing environmentally

friendly policy in a specific national context, by being able to mitigate environmental degradation or by preventing major damage by disaster due to improved forecast mechanisms. It could be argued that by realizing these measures a country could achieve a strategic advantage in the international community.[3] However, by conducting and publishing research, implementing a policy, or realizing a project in the course of bilateral cooperation, spillovers to other parties exist. This is even more apparent when the results are broadly applicable and not specific to the agent's interest. The information spill over to third parties enables them to increase their private benefits and decrease the gap to the competitors in the international community. As a consequence the incentive to invest in these services decreases.
GEOSS, as a research coalition, could function as a remedy to the problem and allows countries to share national data, information systems, or even new technologies on a common platform and to internalize the reciprocal spillovers. The results of this discussion paper confirm this intuition. For a certain spillover rate, profits of coalition members will exceed profits of non-members or profits in a non-cooperative situation. Also a large coalition will yield higher social welfare than smaller coalitions and full cooperation in research maximizes social welfare. The size of the equilibrium coalition depends on the spillover rate.

1.1 Research Objectives & Outline

This discussion paper reviews literature of the branch of Coalition Theory with regards to the formation of research coalitions. The aim is not only to portray the process and challenge of research coalition formation, but also to introduce a set of incentives which could help to overcome the obstacles of spillovers and favour the formation of larger and socially optimal coalitions. The following questions, which are tangent to the challenges and problems of international cooperation in the presence of positive spillovers are central to the analysis:

- In an environment with positive externalities, can a stable grand R&D

[3] I adopt the realist perspective among the theories of international relations and assume that the international system works without an regulatory instance such that states, as central actors of the system, constantly struggle for their survival and hence welfare and profit maximization in an hostil environment. Under these circumstances cooperation is hard to achieve, unless the individual terms are very favourable and profit because states do not trust each other [http://www.weltpolitik.net/; November 2007]

coalition exist which is a social optimum? Which incentives for the formation of a socially optimally sized coalition are given?

- How do spillovers influence the size of the equilibrium coalition?
- Given that coalitions in an environment with positive spillovers tend to be smaller than the socially optimal size, which measures could be integrated in the design of a research coalition to favour broader participation?

The discussion paper is structured as follows: In Section 2 *Formation of Research Coalitions with Positive Spillovers* I present the results of Yi and Shin (2000) who deal with a model of endogenous coalition formation.[4] The model is of rather general nature and provides a framework to understand coalition formation under positive spillovers, assuming an identical intra-coalition or, depending on the amount of coalitions in the equilibrium, inter-coalition spillover rate. They investigate properties of the profit function in a game of R&D cooperation which support the formation of stable coalition structures. Section 3 *Peculiarities of Research Coalitions with Positive Spillovers*, specifies the properties of a R&D coalition. Poyago-Theotoky (1995) introduces a linear-quadratic Cournot oligopoly game to compare the level of cost reduction achieved in a situation of non-cooperation, cooperation, and when an efficient social planner is at work. The results imply that cooperative efforts always exceed non-cooperation. Furthermore, the notion of strategic complements and substitutes with regards to information

[4]Endogenous coalition formation implies that each country has an option to join a coalition or not; hence, the coalition structure is not given exogenously, instead it depicts the outcome of a game. The players accession decision depends on the benefits derived from joining the coalition and the stability of the coalition structure [Yi, 2003, p.81]. According to Hart and Kurz (1983), who provide a comprehensive analysis of endogenous coalition formation, a stable coalition structure can be found by evaluating and comparing each players expected payoff in each possible coalition structure. They consider the entire coalition structure rather than just the individual coalitions because each players payoff depends on the way the other participants are organized. In some situations players might find it convenient to join a coalition, in others they prefer to act separately; all this depends on the configuration of the coalition structure. This implies equally that the overall outcome, the actions of all players in the coalition structure, must be efficient [Hart and Kurz (1983)]. However, the rules of coalition formation, whether only a single or multiple coalitions can form, and whether membership is open or exclusive, are given exogenously [Finus (2003)].

spillovers are explained, and how they affect the size and stability of the equilibrium coalition. The intra-coalition spillover rate is assumed higher than the inter-country/coalititon spillover rate. The results show that spillovers have to be strategic complements to achieve the desired results of high participation. However, the equilibrium size coalition hardly ever coincides with the social optimal size of the coalition. In Section 4 *Expanding a Research Coalition with Positive Spillovers* two suggestions to overcome the problem of free-riding on cooperation, or rather the refusal to enlarge the coalition sufficiently and enhance cooperation are introduced. Based on the framework introduced in Section 3, I introduce the concept of linkage of negotiations to increase participation. The idea is based on the results of Poyago-Theotoky (1995) that members of an equilibrium coalition loose from further expansion of the coalition. Hence, they need to be compensated for instance by externally provided subsidies or, as introduced here, by endogenously linking the public good coalition to a club good agreement. On the basis of the papers by Carraro and Siniscalco (1995, 1997) I present the linkage of the R&D coalition to a trade coalition as to achieve full or nearly full participation. The second proposition stems from Yi and Shin (2000) who suggest multiple coalition formation under two differing membership rules to achieve broader participation. They speak of endogenous coalition formation and investigate the equilibrium coalition structure which emerges under different membership rules. The idea is that by allowing the formation of several coalitions, according to the specific interest of countries instead of focusing only on the formation of one partial or grand coalition, more countries can be motivated to engage in cooperation and to share their data and information. Finally, in Section 5 *Summary and Conclusion* the major results are highlighted and concluding remarks are given.

2 Formation of Research Coalitions with Positive Spillovers

What are the conditions for a stable coalition to exist in an environment with positive externalities? This question will be investigated in the course of a two-stage non-cooperative game amongst n agents. Following rational applies: Countries undertake research to generate a set of improved data and information on the state of the earth, particularly in their national territory

or field of interest, to implement better policies to take 'better' decisions. Consequently, the amount of disseminated and employed data is assumed to be equal to the conducted research.
There are n ex-ante symmetric countries, which at most can form one non-degenerate coalition. In the *first stage* of the game countries choose their level of research, respectively the level of released national data; in the *second stage* they engage in Cournot competition where coalition members maximize their aggregate coalition payoff and non-members their individual payoff. The latter payoff is the second stage Cournot outcome minus the R&D expenditures incurred in the first stage. For simplicity, policies are assumed to be homogenous among all countries; but the implementation costs vary with the amount of data and information available. The more data available, the better the final policy decision and the lower the implementation costs. Cost reduction has diminishing returns [Poyago-Theotoky (1995)].
The agents have at least two possibilities: They can act non-cooperatively and choose their R&D efforts and their policies independently as to maximize their individual payoffs. When deciding on their R&D investment they take other countries' R&D expenditures as given. Secondly, countries can act cooperatively and form a R&D coalition with $k \leq n$ members. Coalition members choose their R&D expenditures and paths cooperatively as to maximize their joint profit. They decide independently on the amount of policies and decisions implemented [Poyago-Theotoky (1995)].
The parameter β denotes the degree of information spillover between countries. Usually the intra-coalition spillover β^c is assumed to be one, whereas the inter-country spillover from the coalition to the non-members and vice versa, takes a value $0 \leq \beta^o \equiv\leq 1$; $\beta^o \equiv \beta$ [Poyago-Theotoky (1995)]. This property is applied in Section 3. The general framework introduced in this section and the analysis of Yi and Shin (2000) in Section 4 assume an identical intra-coalition and inter-country/inter-coalition spillover rate, $\beta^o = \beta^c$.
x_i depicts country i's R&D investment; where $\mathbf{x} \equiv (x_1, ...x_n)$ is the investment vector, and $X \equiv \sum_{i=1}^n x_i$ be total R&D investment. The profits depend only on the individual investments and on the aggregate investment and is thus $V^i(\mathbf{x}) \equiv V(x_i, X)$. The countries' profits are concave in x_i. Coalition members choose their R&D investment as to maximize their joint profits $\sum_{i=1}^k V(x_i, X)$ [Yi (2003)].

The next subsections introduce assumptions on the profit function and the equilibrium coalition structure.

2.1 Coalition Structure and the Amount of R&D Investment

Assumption 1. $V_X(x_i, X) > 0$

This assumption by Yi and Shin (2000) captures the public good nature of research investment. An increase in a country's R&D investment generates positive spillovers and raises other countries' profits. In the absence of R&D cooperation, when there is no way to internalize these spillovers countries will underinvest.

Assumption 2. *There are three points to consider:*
(a) $V_{xx}(x_i, X) + kV_{xX}(x_i, X) < 0$
(b) $V_{xx}(x_i, X) + (k + N)V_{xX}(x_i, X) + kNV_{XX}(x_i, X) < 0$
(c) $V_X(x_i, X)+kV_{xX}(x_i, X) > 0$ *and* $V_{xx}(x_i, X)-k[V_{xxx}(x_i, X)+kV_{xxX}(x_i, X)] \leq 0$ *with* $k = 1, ..., N$

Point (a) is crucial and implies that a size-k coalition's profit function is concave in member's investment, holding the other investment $(X - x_i)$ constant. Initially profits increase with investment and then decrease. (b) Whenever members of a coalition increase their investments exogenously, the industry's investments increase in the equilibrium as well. According to Yi and Shin (2000), this works as stability condition. (c) states that a large coalition's total investment is more sensitive to changes in membership than a small coalition's total investment [Yi and Shin (2000)].[5]

Assumption 3. $CS(\boldsymbol{x}) = CS(X)$ *and* $CS_X(X) > 0$

Consumer surplus (CS) depends only on the total worldwide R&D investments; an increase in total R&D investments raises consumer surplus. Hence, the more countries cooperate, the more R&D will be generated to raise consumer surplus.

The size of the coalition and the composition of the coalition structure are decisive for the realised R&D. Yi and Shin (2000) introduce the term 'concentration of a coalition structure' to the analysis to facilitate the comparison of equilibrium coalition structures under different rules of coalition formation [Finus and Rundshagen (2003)]. They assume that coalition formation is an endogenous process and that several research coalition can co-exist and

[5] For a detailed proof see Yi and Shin (2000) Appendix A

compete in a coalition structure at a time. Where n_i denotes the size of the coalition D_i with $i = 1, ..., m$; each country can belong to only one research coalition at a time. The resulting coalition structure is $C \equiv \{D_1, D_2, ..., D_m\}$. All affected countries are identical such that only the size of the coalition matters and the structure can be described as $C \equiv \{n_1, n_2, ...n_m\}$. In cases where only one partial research coalition exists, is a special case and can be analyzed within this broader framework denoting $C = \{n_i, 1, ...1\}$.[6]
The concentration of a coalition structure plays a critical role in the analysis of a stable coalition structure and the depiction of positive externalities. The following, somehow intuitive, definition has been proposed by Finus and Rundshagen (2003, p.204)

Definition 1. *Concentration of a Coalition Structure:*
A coalition structure $C = \{n_1, n_2, ...n_m\}$ *is a concentration of* $C' = \{n'_1, n'_3, ...n'_{m'}\}$*, where* $m' \geq m$*, if one can obtain* C *from* C' *by a finite sequence of moving one member at a time from a coalition in* C' *to another coalition of equal or larger size.*

Finus and Rundshagen (2003) provide an example: A coalition structure $(6, 5)$ is more concentrated than a coalition structure $(5, 5, 1)$. Concentration allows only for a partial ranking of coalition structures. For instance $(4, 3)$ and $(5, 11)$ cannot be ranked under concentration.

According to Yi and Shin (2000) there exists a unique interior equilibrium. The per-member equilibrium R&D investment of a member in coalition n_i is $x(n_i, C)$; $X(n_i, C) \equiv n_i x(n_i, C)$ is the total R&D investment of coalition n_i and $X(C) \equiv \sum_{i=1}^{m} n_i x(n_i, C)$ is the industry investment under given coalition structure $C = \{n_1, n_2, ..., n_m\}$.
The per-member equilibrium R&D investment satisfies a set of conditions, which in turn highlight the public good character of the research coalition:

Assumption 4. $x(n_i, C) > x(n_j, C)$ *for* $n_i > n_j$ *in any* $C = \{n_1, n_2, ..., n_m\}$.

In any coalition structure a member of a large research coalition invests more in R&D than a member of a small coalition or a singleton coalition. A coalition member internalizes the positive externalities that its investments generates on a member countries. Hence, a member or a large coalition

[6] According to Yi (2003) this game can be denoted as Single Coalition Formation Game and is based on a paper of D'Aspremont et al. (1983), who investigate the stability of a price-leadership cartel

invests more in research than a member of a small coalition [Yi and Shin (2000)].

Assumption 5. *$X(C) < X(C')$, where C' is a concentration of C. In particular, $X(C) < X(\{N\})$ for any $C = \{n_1, n_2, ..., n_m\}$, $n_1 < N$.*

If the research coalition becomes more concentrated the industry investment increases. In particular, industry investment are highest under the grand coalition than under any other coalition structure. Larger coalitions increase their research since they internalize the positive externalities on the new members.

2.2 Coalition Structure and Countries' Payoff

The $\pi(n_1; C)$ denotes the per-member equilibrium profit of a size n_1 coalition in the coalition structure $C = \{n_1, ..., n_m\}$. The aggregate payoff of the size n_1 coalition is $n_i\pi(n_i; C)$ [Yi (2003)]. According to Yi and Shin (2000), the profit function has to fulfil three conditions which help to derive an equilibrium coalition structure. The intra and inter-coalition spillover rate is assumed to be equal.

- (P.1) $\pi(n_k; C) < \pi(n_k; C')$, where C' is more concentrated than C and $n_k \in C$ and C'.

If the coalition structure becomes more concentrated, countries which are not involved in the change of the coalition structure and remain free-riders earn higher payoffs.

- (P.2) $\pi(n_j; C) > \pi(n_i; C)$, where $n_i > n_j$ in any $C = \{n_1, n_2, ...n_m\}$.

Singleton players or small coalitions always earn a higher payoff than the coalition members, since they can free-ride on the efforts of the larger coalition in the structure. This depends also on the degree of spillovers.

- (P.3) $\pi(n_j; C) < \pi(n_j - 1; C')$, where $C = \{n_1, n_2, ..., n_m\}$, $C' = C \backslash \{n_i, n_j\} \cup \{n_i + 1, n_j - 1\} = \{n_1, ..., n_{i+1}, ..., n_{j-1}, ...n_m\}$, and $n_i \geq n_j \geq 2$.

If a member of a research coalition joins a larger or equal-sized coalition, the remaining members of the deviator's research coalition earn a higher payoff. Considering the results of Assumptions 4 and 5 that a member of a large research coalition invests more than a member of a small coalition, the above conditions on the payoff function are easily traceable. To demonstrate how these conditions work, Yi (2003) has introduced Lemma 1.

Lemma 1. *Research coalitions for internalization of R&D externalities satisfy (P.1)-(P.3) under Assumption 1 and 2.*

Again, a member of a research coalition can internalize the positive externalities its investments generate on member countries. Hence, a member of a large coalition invests more in R&D than the member of a small coalition. The members of the small coalition or the singleton players free-ride on the higher R&D investment of the large coalition, and earning higher profits due to (P.2). The same reasoning applies for coalitions which are merging or players who join a larger or equal size coalition. They increase their investment as the positive externalities of the new members are internalized. Members who are not involved in the change of coalition structure benefit by free-riding on the increased industry investment due to (P.1) and (P.3) [Yi (2003)].

2.3 Stable Coalition Structures

Yi and Shin (2000) characterize stable coalition structures under Assumption 1 and 2 as long as (P.1)-(P.3) holds:

Definition 1. *Stand-alone stability:*
The size-n_i coalition in $C = \{n_1, ..., n_i, ..., n_m\}$ is stand-alone stable iff $\pi(n_i; C) \geq \pi(1, C_i)$ where $C_i = C \backslash \{n_i\} \cup \{n_i - 1, 1\} = \{n_1, ..., n_i - 1, ...n_m, 1\}$. A research coalition is stand-alone stable if a member earns a lower profit by leaving it to form a one country coalition, and by holding the rest of the coalition structure fixed. The research coalition structure $C = \{n_1, ..., n_m\}$ is stand-alone stable iff all m coalitions in it are stand-alone stable.

3 Peculiarities of Research Coalitions with Positive Spillovers

In the previous section conditions which support coalition formation are identified. To describe the advantages of coalition formation versus the non-cooperative situation and to illustrate the forces at work to decide the equilibrium size of a research coalition, I introduce a linear-quadratic Cournot

model based on the paper of Poyago-Theotoky (1995).
The two-stage game introduced in Section 2 remains; the spillover rate takes the value $0 \leq \beta^o \equiv\leq 1$; $\beta^o \equiv \beta$. There are n identical countries which implement environmentally friendly policies. The policies are costly. Improved data and information, which stem from either individual or collective research efforts, support better policy decision making. Each level of policy Q yields a value of foregone damage P.

$$P = D - b\sum_{i}^{n} q_i$$

where $i = 1, ...n$, $b = 1$, and $D > 0$ is a constant parameter. It is assumed that there are constant returns to scale in policy implementation and the costs of policy implementation are affected by the amount of R&D that each country undertakes to generate improved data. The unit costs of policy implementation for country i are given as

$$c_i = A - z_i - \beta\sum_{i \neq j} z_j$$

where $0 < A < D$ and $z_i + \beta \sum z_j \leq A$. z_i is the cost reduction achieved by country i's research effort x_i and z_j is the cost reduction achieved by the remaining countries due to spillovers $0 \leq \beta \leq 1$. The cost of doing R&D is given by $c(z_i) = \gamma z_i^2/2$ with $\gamma > 0$. Hence, there are diminishing returns to cost reduction [Poyago-Theotoky (1995)].

3.1 Non-cooperative Case

The following results, on the basis of Poyago-Theotky (1995), resemble the n-player Cournot game. The players maximize their profits $\pi_i(q_i, q_{-i}) = p(q_{-i}, q_i)q_i - c_i q_i$ simultaneously, anticipating the produced quantity of their fellow players, q_{-i}. The second-stage Cournot profit of country i, $i = 1, ...n$, can be written as

$$\pi_i = [\frac{D - nc_i + (n-1)c_j}{(n+1)}]$$

where $i \neq j$. The unit costs of country i is given by $c_i = A - z_i - (n-1)z_j$ and for the $(n-1)$ remaining countries they are given by $c_j = A - z_j - \beta z_i - \beta(n-2)z_j$. These expressions are substituted in π_i, the expenditures of R&D

investment are deducted and the equation is maximized with respect to the country's R&D output, z_i:

$$\pi_i = [\frac{(D-A) + (n - \beta n + \beta)z_i + (2\beta - 1)(n-1)z_j}{(n+1)}]^2 - \frac{\gamma z_i^2}{2}$$

After this expression has been maximized with respect to z_i, $\delta\pi_i/\delta z_i$, the equilibrium value $\bar{z}$ has to be found, assuming that all countries are identical and achieve a symmetric cost reduction due to R&D:

$$\bar{z} = \frac{2(D-A)(n - \beta n + \beta)}{[\gamma(n+1)^2 - 2(n - n\beta + \beta)(1 + \beta n - \beta)]}$$

According to Poyago-Theotoky (1995) and for $\beta = 0$, the equilibrium value of cost reduction $\bar{z}$ takes the form $\bar{z} = 2n(D-A)/\gamma(n+1)^2 - 2n$; while for full spillovers, $\beta = 1$, $\bar{z} = 2(D-A)/\gamma(n+1)^2 - 2n$, such that $\bar{z}[\beta = 0] > \bar{z}[\beta = 1]$. R&D effort is greater in the absence of spillovers. Without spillovers countries can lower their costs for implementing policies and increase their significance in the international community. They create a gap between themselves and the other countries. In the case of full spillovers R&D still reduces implementation costs and is desirable, but there exists no strategic advantage in 'being ahead' of other countries, and the R&D efforts are evidently reduced.

3.2 Cooperative Case

A k coalition is formed with $2 \leq k \leq n$. There is full information sharing among the coalition members; from the coalition to the remaining $(n-k)$ members and vice versa $0 \leq \beta \leq 1$ applies.
For simplicity, assume from now on: $z_i = z_{-i} = z$ with $i = 1, ...k$ since the member countries are identical; and $z_j = z_{-i} = \bar{z}$ with $j = 1 + k, ...n$.
For country i the unit costs of production, g, depend on the amount of R&D, z_i, it does, the amount of the other member countries z_{-i}, and the amount the remaining $(n-k)$ countries, z_j: $g = A - kz - \beta(n-k)\bar{z}$.
The unit costs h for country j, depend equally on the amount of R&D, the amount of R&D, z_{-j}, the remaining $(n-1-k)$ countries and the R&D of coalition members: $h = A - \bar{z} - \beta(n-k-1)\bar{z} - \beta kz$.
The second stage Cournot profit is derived analogous to the non-cooperative

case and can be written as:

$$\pi_{i,c} = [\frac{D + (n-k)h + (k-1)g - ng}{(n+1)}]^2 \tag{3.1}$$

Hence, the R&D output z is chosen as to maximize the joint payoffs net of R&D expenditures:

$$max_z \frac{k}{(n+1)^2}[D + (n-k)h + (k-1)g - ng]^2 - (\frac{k\gamma z^2}{2})$$

The unit costs h and g are substituted and the term is rearranged to[7]

$$(D-A) = -\bar{z}(n-k)(2\beta-1) + z[\frac{\gamma(n+1)^2 - 2k^2[(n-k)(1-\beta)+1]^2}{[2k(n-k)(1-\beta)+1]}] \tag{3.2}$$

A similar expression is derived for the remaining $(n-k)$ agents who do not participate in the coalition. The unit cost of production s for country j are dependent on the amount of R&D of coalition member i, z_i, on its own amount z_j and the amount of the remaining $(n-k-1)$ countries z_{-j}. In this case $z_i = z$, $z_{-j} = \bar{z}$, $z_j = \tilde{z}$ and the unit cost are rewritten as $s = A - \tilde{z} - \beta kz - \beta(n-k-1)\bar{z}$. Any of the remaining $(n-k-1)$ countries face unit costs t: $t = A - \bar{z} - \beta kz - \beta\tilde{z} - \beta(n-k-2)\bar{z}$. Finally, coalition members bear unit costs of v written as: $v = A - kz - \beta\tilde{z} - \beta(n-k-1)\bar{z}$. Given these assumptions of the unit costs the resulting second stage Cournot profits for non-members are:

$$\pi_{j,c} = [\frac{D + (n-k-1)t + kv - ns}{(n+1)}]^2 \tag{3.3}$$

In the first stage the non-member country chooses R&D output as to maximizes their second stage profits net of R&D expenditure:

$$max_{z_j=\bar{z}}(n+1)^{-2}[D + (n-k-1)t + kv - ns]^2 - (\gamma z_j^2/2).$$

t,v and s have to be substituted in the above expression. After the expression has been maximized after $z_j = \bar{z}$ symmetry among $\tilde{z} = \bar{z}$ has to be imposed,

[7]According to Poyago-Theotoky (1995), the second order condition requires that $\gamma > 2k^2[(n-k)(1-\beta)+1]^2/(n+1)^2$.

yielding[8]:

$$(D-A) = -k[\beta(k+1)-k]z+[\frac{\gamma(n+1)^2 - 2[n(1-\beta)+\beta][\beta(n-k)+(1+k)(1-\beta)]}{2[n(1-\beta)+\beta]}]\bar{z} \tag{3.4}$$

To get the equilibrium values of cost reduction z of coalition members and $\bar{z}$ of non-members, equation (3.2) and (3.4), have to be solved simultaneously. Poyago-Theotoky (1995) shows in the Appendix of her paper analytically for $z > \bar{z}$ that a research coalition always generates more R&D output and spends more on R&D than the non-participating countries. Countries in the coalition entirely internalise the spillover externality. The equilibrium amount of cost reduction varies with the size of the spillover rate, which is depicted in Figure 1. It is easy to see that the coalition achieves a higher total cost reduction for all β, even though cost reduction for the coalition members decreases with an increasing β. Wheras non-members enjoy an increase in cost reduction due to spillovers. Poyago-Theotoky (1995) uses numerical simluations with values: $D = 300$, $A = 50$, $\gamma = 50$, $n = 10$.[9] Each country in the coalition spends more resources, achieves a higher level of research output and gains a larger cost reduction than each of the non-cooperative countries. Each country in the coalition can perform research at a lower cost than the independent countries. Since all coalition members enjoy the same level of cost reduction they do not have a strategic advantage over each other, which increases the incentive to invest in research and achieve an even higher cost reduction. In the non-cooperative case, cost reduction increases up to $\beta = 0.5$ and decreases thereafter. The same reasoning for total cost reduction applies for the profits of the coalition members and non-members depicted in Figure 2. Members clearly enjoy higher profits than non-members, but their profits are assimilating for an increasing β.

[8] According to Poayago-Theotoky (1995) the second order condition requires that $\gamma > 2[n(1-\beta)+\beta][\beta(n-2k-1)+(k+1)]/(n+1)^2$.

[9] Poyago-Theotoky (1995) concludes that in order to obtain positive values of R$D output $\gamma > 8(n+1)^2/27$; in the case of $n = 10$ $\gamma = 35.85$; in this example round up to $\gamma = 50$.

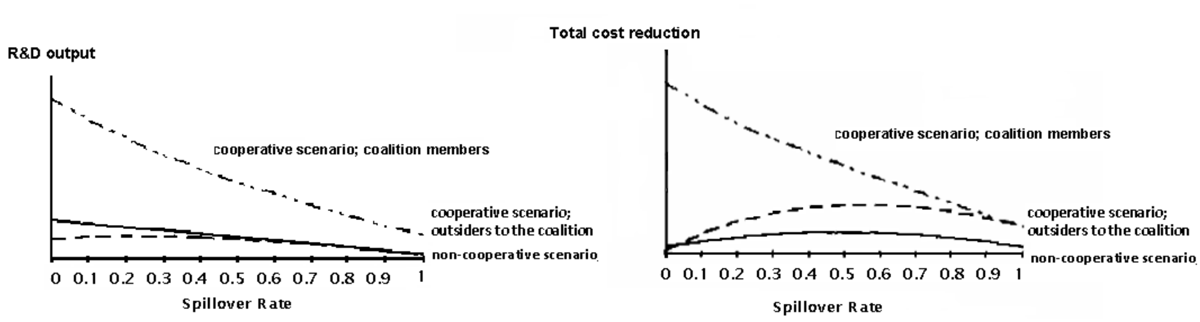


Figure 1: R&D output and total cost reduction by spillover rate β [Poyago-Theotoky (1995)].

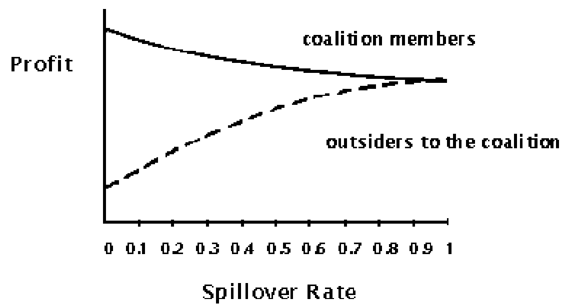


Figure 2: Profit dependend on spillover rate β in a situation of cooperation. [Poyago-Theotoky (1995)].

3.3 Socially Optimal and Equilibrium Size

In order to derive the socially optimal size k for the research coalition, a social planner maximizes the industry profits:

$$max_k[\sum_{i=1}^{k} \pi_{i,k}(\mathbf{q}, \mathbf{z}) + \sum_{j=k+1}^{n} \pi_{j,c}(\mathbf{q}, \mathbf{z})]$$

where $\mathbf{q} = (q_i, q_j)$ and $\mathbf{z} = (z_i, z_j)$, $i = 1, ..., k$ and $j = k+1, ..., n$. According to Poyago-Theotoky (1995) total industry payoff is convex and increasing in k for all values of β.

The equilibrium size of the coalition is chosen as to maximize the members' payoff. After all accession to the coalition is only granted as long as it is profitable.
The equilibrium size coalition k^e is that size k where no member has an incentive to deviate: $\pi_{i,k}(k^e) > \pi_{i,k}(k^e - 1)$; and no free-rider can profit by acceding to the coalition: $\pi_{i,k}(k^e + 1) < \pi_{i,k}(k^e)$. Poyago-Theotoky (1995) refers to this as a 'entry-blocking' coalition. Table 1 shows this results for the same simulation vales as before. This implies that for certain levels of

β	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
k^e	6	6	6	6	6	6	6	6	7	9	10
k^S	10	10	10	10	10	10	10	10	10	10	10

Table 1: Equilibrium k^e and optimum k^S size of the research coalition [Poyago-Theotoky (1995)].

spillovers there is not enough cooperation. Countries focus on their individual profits when blocking entry to an additional country, rather than taking into account the social profits which are maximized when entry is granted to nearly all countries [Poyago-Theotoky (1995)].

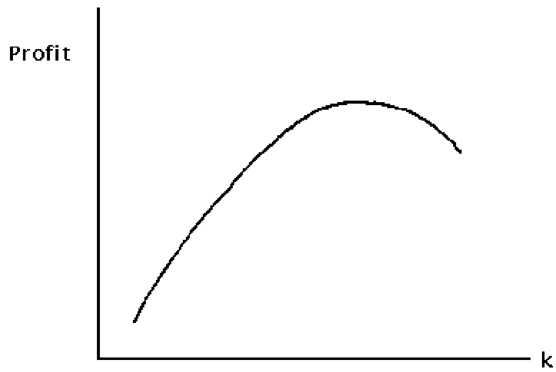


Figure 3: A schematic depiction of the coalition's profit. The profits of the coalition depend on the size of the coalition [Poyago-Theotoky (1995)]

3.4 Evaluation

Poyago-Theotoky (1995) concludes that, depending on the value of spillovers between the coalition and the non-members, three different types of equilibria exist:

- $\beta \leq 0.5$; R&D is a strategic substitute for both coalition members and non-members [Poyago-Theotoky (1995)]. Whenever the coalition increases their R&D expenses and achieves a higher cost-reduction z, the marginal profitability of the non-coalition members decreases. Their cost-reduction capability does not necessarily increase or if so at a lower rate, such that the coalition have an advantage, and vice versa [Bulow et al. (1985)].

- $0.5 \leq \beta \leq k/k+1$; R&D becomes a strategic complement for the coalition members but remains a strategic substitute for the non-cooperating countries [Poyago-Theotoky (1995)]. Whenever the coalition achieves a cost reduction z, the research effort $\bar{z}$ of the non members does not necessarily increase or remains the same, whereas whenever the non members achieve a cost reduction, the coalition profits as well [Bulow et al. (1985)].

- $k/k+1 < \beta < 1$; R&D is a strategic complement for all coalition members [Poyago-Theotoky (1995)]. While coalition members achieve a cost reduction, the non members achieve just the same reduction of costs. According to Yi and Shin (2000, p.248), this case favours coalition formation and (P.1)-(P.4)[10] hold for β close to 1. Furthermore the results of Section 2 and Section 4.1 apply.

Finally the question on the effect of the spillover rate on the equilibrium size of the coalition remains. According to Poyago-Theotoky (1995), the profits of an individual coalition member are usually increasing and concave in k, for all values of spillovers, reaching a coalition size of $k < n$. Expanding the research coalition has two effects: As the number of members increases a given R&D expenditure is spread among countries, lowering the cost of R&D and increases per country profit. On the other hand, increasing the coalition by granting access to a member that has a lower R&D productivity and a smaller cut back of production cost means sharing the market with a less

[10] For a definition of (P.4) see Section 4.2.2

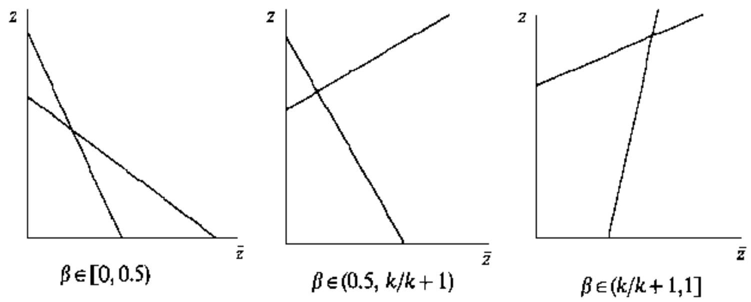


Figure 4: These graphs illustrate how cost reduction depends on the size of the positive externalities. z refers to the cost reduction of coalition members, $\bar{z}$ refers to cost reduction of non-members and β refers to the spillover rate outside the coalition [Poyago-Theotoky (1995)]

efficient co-venturer. This presses down the average profit and explains the concavity of the per country payoff.
Considering β takes the form of a strategic substitute: There are not sufficient spillovers and the gap between the coalition and the non-coalition members is quite large. Hence, allowing a non-member to accede will dreadfully press the average payoff of the coalition members. The coalition will block entry and the equilibrium size of the coalition will be a lot smaller than the optimal size.
When spillovers take the form of a strategic complements, then an increase in R&D investment of the coalition will also benefit the non-coalition members. The gap between the non-members and members is not sufficiently large and expanding the coalition will not jeopardise the per member payoff. The equilibrium size and optimal size eventually coincide.
Yi and Shin (2000) conclude:

Lemma 2. *Assumptions 1-3 hold in the linear-quadratic model of cost-reducing R&D in Cournot oligopoly for $\beta > 0,5$ and $b\gamma > 2$.*[11]

Thus, β has to take the form of strategic complements to support successful coalition formation.

Data and information of the GEOSS members rather take the form of strategic complements; national information can be used complementary and

[11] Yi and Shin (2000) provide the proof in Appendix B of their paper

also the quantity of information can lead to better policies and results, such that there is a chance that the coalition will be rather large and profitable. Nevertheless β can reflect the willingness to disseminate data and information and can take a rather low value, such that the question remains: which incentive system has to be given to increase the coalition or trigger existing members to increase the spillover rate to eventually reach a social optimal size? This question will guide the third part of the working paper.

4 Expanding Research Coalitions with Positive Spillovers

The equilibrium size of research coalitions in games with positive externalities depends on the degress of spillovers. In environmental coalitions the behaviour of free-riders is decisive for the coalition size, which is usually smaller than the socially optimal size.[12] The equilibrium derived in research coalitions is of the 'entry blocking' type. It forms where one more member decreases the payoff of the current members [Poyago-Theotoky (1995)]. As to increase the size of research coalitions various measures have been proposed. Subsidies are usually suggested, which compensate the coalition members for incurring the cost when granting access to one more member. Nevertheless, subsidies are usually assumed to be externally implemented.

In this section, I introduce some results of Carraro and Siniscalco (1995, 1997) who have introduced an endogenous possibility to increase the size of a club good coalition. Linking the research coalition to a, for example, free trade agreement, which is of exclusive nature, could compensate the initial coalition members for expanding the coalition.

Another interesting proposition stems from Yi and Shin (2000), who suggest

[12]Environmental coalitions deal equally with the production of a public good i.e. clean air, decrease environmental degradation; hence, bear the similar characteristics as the framework in Section 2. They can be equally depicted as two-stage games; where in the first stage membership is decided and in the second stage the payoff is maximised, i.e.: the optimal emission vector is decided. The public good nature of environmental coalitions makes them prone to free-riding. Whenever the reaction function of free-riders takes the orthogonal form, and the free-riders display supportive behaviour for the coalition and merely enjoy the fruits of cooperation, even full cooperation could be achieved; whereas, non-orthogonal free-riding,- whenever free-riders offset the efforts of the coalition by i.e. increasing emissions, decreases the profits of cooperation and yields a rather small coalition [Carraro and Siniscalco (1995, 1997)].

to increase the number of members by allowing the formation of multiple coalitions. To achieve this, they transform the previously assumed club good game with two different spillover rates, one for coalitions members ($\beta^c = 1$) and for outsiders ($0 \leq \beta^o \leq 1$), into a public good game by discarding the assumption that the spillover rate inside and outside the coalition varies. Hence, $\beta^c = \beta^o \equiv \beta$, the spillover rate is either equal or nearly equal. Here the typical Prisoners' Dilemma free-rider logic applies, where free-riders gain a higher payoff than coalition members and are therefore unwilling to join the coalition. Incentives have to be provided to make accession to the coalition attractive for free-riders.

4.1 Linkage of Negotiations

Carraro and Siniscalco (1995, 1997) suggest designing a negotiation mechanism in which countries do not only negotiate on the public good issue, i.e. the emission abatement, but also on another interrelated issue.
Similarly, in the prevIsous section Poyago-Theotoky (1995) has shown that an equilibrium coalition in a club good game on R&D cooperation is usually smaller than the socially optimal size for $\beta < 1$. The coalition members' profits decrease due to low productivity of an additional member. To increase the coalition and reach the socially optimal size of full participation, the inital members have to be compensated for the loss incurred when granting access to one additional member. This could be achieved by linking the R&D agreement to another club good agreement, i.e. a trade agreement which opens a new market for the coalition members. Besides the profit derived by nationally implemented policies and decisions taken on the environment and natural resources and the spillover rate of other countries, there exists an industry with firms who act according to the country's legislation. Suppose in each country resides one firm which produce an homogeneous good and which is granted access to the newly developed market. Further consumers' demand is stimulated by their wellbeing. As it has been subject to recent research, wellbeing is heavily linked to the natural environment with a focus on parks, forests, gardens etc.[13], whose conservation and utilization depends on the implemented policies and decisions made due the research coalition. Profits in the trade coalition are humped-shaped; initially increasing with an additional member, then decreasing. By selling more goods to more consumers

[13] Compare Newton (2007)

the profits can be increased and a strategic advantage over the non-member firm/countries can be singled out.Clearly, the more countries accede to the coalition this advantage decreases and due to more competition, the price decreases as well which affects profits.

According to Carraro and Siniscalco (1995), two negotiations are linked when signing the first agreement is conditional on signing the other one, and vice versa. The linkage thus changes the rules of the game, the strategy space and the payoff functions. Now $P^1(j_1^*)$, in the previous section $\pi_{j,c}$, is the payoff of the j_1^* countries which join the R&D agreement and $Q^1(j_1^*)$ is the payoff of the non-signatories. Similarly, $P^2(j_2^*)$ and $Q^2(j_2^*)$ are defined for the trade agreement. The payoff of the countries signing the joint agreement is $P^u(j_u^*)$, and of the non-signatories $Q^u(j_u^*)$. The set of signatories is defined as J^1, J^2, J^u and J_0^1, J_0^2, J_0^u is the set of non-signatories.
A coalition is profitable when $P^k(j_k^*) \geq 0$ for $k = 1, 2, u$ [Carraro and Siniscalco (1995)]. According to Poyago-Theotoky (1995), a stable equilibrium size coalition j^e is that size j where no member has an incentive to deviate: $\pi_{i,j}(j^e) > \pi_{i,j}(j^e - 1)$; or to let one more country accede to the coalition: $\pi_{i,j}(j^e + 1) < \pi_{i,j}(j^e)$. Poyago-Theotoky (1995) refers to this as 'entry-blocking' coalition because profits decrease when access to one addition member is granted. Carraro and Siniscalco (1995) analyze the expansion of the coalition and consider $J^1 \in J^u$:

Definition 2. *Linking two negotiations increases the dimension of the stable environmental coalition if $j_u^* > j_1^*$. The move to a larger stable coalition is profitable for the j_1^* countries belonging to the stable research coalition if:*

$P^u(j_u^*) \geq P^1(j_1^*) + P^2(j_2^*)$ *when* $J^1 \in J^u$, $J^1 \in J^2$
$P^u(j_u^*) \geq P^1(j_1^*)$ *when* $J^1 \in J^u$

The linkage occurs when it increases the welfare of the signatories vis-a-vis the case of separated negotiations. It may not be Pareto-optimal, and countries which do not sign the agreement may loose with respect to the situations in which they belonged to one of the two agreements. Carraro and Siniscalco (1995) consider the signatories of the second agreement:

Definition 3. *The welfare of countries which do not belong to the research agreement, but belong to the other one, does not decrease when the joint coalition is formed if:*

$P^u(j_u^*) \geq P^2(j_2^*)$ *when* $J^2 \in J^u$
$Q^u(j_u^*) \geq P^2(j_2^*)$ *when country* $i \in J^2$, $i \notin J^u$

To achieve Pareto-optimality, the joint coalition must not decrease the welfare of those countries who did not belong to any coalition. Q_0 is the payoff of these countries before the coalition is joined and Carraro and Siniscalco (1995) conclude:

Definition 4. *Linking two negotiations is Pareto-optimal if the conditions of Definition 2 and Definition 3 hold and if:*

$P^u(j_u^*) \geq Q_0$ *when* $J_0 \in J^u$
$Q^u(j_u^*) \geq Q_0$ *when country* $i \in J_0$, $i \notin J^u$

Proposition 1. *If* n*, the number of negotiating countries, is the dimension of* J^2 *and* J^u*, which implies that all countries join the second and the joint agreement, and if* $P^u(n) \geq P^1(j_1^*) + P^2(n)$, $j_1^* < n$*, then the linkage of the two negotiations expands the research coalition and is Pareto-optimal.*

Proof: By assumption $j_u^* = n > j_1^*$, which implies that the linkage expands the environmental coalition. $P^k(j_k^*) \geq 0$, $k = 1, 2, u$, by the profitability condition, hence, $P^u(n) \geq P^1(j_1^*) + P^2(n) > 0$. $J^u = J^2$ and J_0^1 is empty, there exists no non-signatory. This makes only following conditions relevant:
$P^u(j_u^*) \geq P^1(j_1^*) + P^2(j_2^*)$ when $J^1 \in J^u, J^1 \in J^2$
$P^u(j_u^*) \geq P^1(j_1^*)$ when $J^1 \in J^u$
$P^u(j_u^*) \geq P^2(j_2^*)$ when $J^2 \in J^u$ (Q.E.D.)

Through linkage of two issues countries in the R&D coalition are compensated for the effort to let one more country join their coalition.Due to the very simplified framework, the specific shapes of the results of the linkage in reality are unclear. However, following aspects shed light on how issue linkage could manifest in reality.
Trade effect: The trade coalition enables access to a broader market such that firms' profits, market share, and consumer surplus increase, but decreases as j approaches n. Suppose only the initial members of the R&D coalition accede to the trade coalition. Under these circumstances full cooperation can be achieved when the payoffs of the trade coalition compensate the R&D members sufficiently. If each newly entered member of the research coalition enters the trade coalition as well, the profits of the trade coalition

decrease and coalition members are not suffciently compensated for expanding the coalition further. In this case, the resulting expanded coalition might be smaller than when only initial members are in the trade coalition.
Welfare effect: The welfare effect demonstrates that research coalition with full membership maximize social and environmental welfare, which in turn has a positive influence on consumers' wellbeing and purchase capacity, which positivley influences the results of the trade coalition.
Environment effect: The environmental effect shows that an increase in production and trade harms the environment and negativly affects natural resources. On the other hand, the policies implemented by GEOSS help protect the environment.
The interplay of these effects determines the outcome of issue linkage. Linkage of negotiation is a powerful tool to adress the expansion of a coalition. There is a risk of increasing complexity and unintended consequences. Hence, the concept should preferably be applied to bilateral negotiations, when issues can be chosen carefully such that they are roughly offsetting. This requires further that countries have complementary needs, otherwise the agreement will not come into force [Cesar and de Zeeuw (1996), p.160].

4.2 Multiple Coalition Formation

Yi and Shin (2000) allow for the endogenous formation of multiple research coalitions given various rules of coalition formation. Allowing for multiple coalitions to form in the equilibrium acknowledges the heterogeneity of countries, which have different interest and might be more agreeable to the idea to form a coalition with a like-minded group of countries with i.e. similar environmental problems and research foci.
Yi and Shin (2000) assume an intra-coalition spillover rate equal to the inter-country/inter-coalition spillover rate. Hence, they discard the club good nature of a research coalition and apply the framework outlined in Section 2. The individual benefits are simply derived by internalizing the research results without giving importance to the strategic advantage. A strategic advantage emerges by appropriating private benefits due to information or research which is exclusively accessible for the coalition members. Here, the reasoning of the game changes and agents are facing a public good problem,because policies on the environment provide a public good, which inflichts equal spillovers on all agents. Apart from the fact that policies are of

public good nature, the realised projects and decisions can equally be copied by non-members without having to incur the effort of being in the coalition and sharing data. In this analysis only the sum of policies plays a role and affects the country's individual payoff. Outsiders to the coalition enjoy a higher payoff (composed by the policies implemented by the coalition members and the policies they can implement given the knowledge of the other countries). The model is in accordance with the model of Poyago-Theotoky (1995) for a spillover rate close to one, hence for strategic complements. Strategic complements still imply that the more countries are willing to share their data, the better the response will be.
Yi and Shin (2000) introduce two different membership rules for a game of multiple coalition formation and present the resulting equilibrium structures for $0.5 < \beta \leq 1$. The framework is in accordance with the assumptions outlined in Section 2.

4.2.1 Exclusive Membership Game

The idea of the so-called exclusive membership game stems from Hart and Kurz (1983) who refer to it as Δ-Game. According to Yi and Shin (2000), the idea of the game is the following: Each country announces simultaneously a list of players with whom it is willing to form a research coalition; the countries who announce exactly the same list of members belong to the same coalition. Country i's strategy is to choose a set of players S^i, a subset of $S \equiv \{P_1, P_2, ..., P_N\}$ where P_i denotes country i. Given the countries' announcements $\alpha \equiv (S^1, S^2, ...S^N)$, the resulting coalition structure is $C = \{D_1, D_2, ..., D_m\}$, where country i and j belong to the same coalition D_k if, and only if, $S^i = S^j$; that is they choose exactly the same list of players. For example, if $\alpha = (\{P_1, P_2\}, \{P_1, P_2\}, \{P_3\}, \{P_3, P_4\})$ the resulting coalition structure is $C = \{2, 1, 1\}$ and country 1's and country 2's payoff are $\pi(2; \{2, 1, 1\})$ whereas country 3's and country 4's payoff equal $\pi(1; \{2, 1, 1\})$. Country 4 cannot join country 3 without its consent, whereas country 3 can join country 4's singleton coalition [Yi and Shin (2000)].
To derive an equilibrium, Yi and Shin (2000) employ the above introduced conditions on the payoff function and further assume,- in contrast to the previous chapter, an uniform spillover rate.
The first step is to show that at least one stand-alone stable Nash equilib-

rium[14] can exist:

Proposition 2. *$C = \{n_1, n_2, ...n_m\}$ is a Nash equilibrium coalition structure if and only if it is stand-alone stable. Since $C = \{1, 1, ..., 1\}$ is stand-alone stable by definition, a Nash equilibrium coalition structure exists in this game.*[15]

Suppose C is stand-alone stable and is supported by following strategy profile: $\alpha = (S^1, S^2, ...S^N)$ where $S^1 = ... = S^{n_1} = \{P_1, ..., P_{n_1}\}$ and $S^{n_1+1} = ... = S^{n_1+n_2} = \{P_{n_1+1} = ..., P_{n_1+n_2}\}$ and $S^{t+1} = ...S^N = \{P_{t+1}, ...P_N\}$ where $t = N - \sum_{i=1}^{m-1} n_i$. In this scenario no country can join another research coalition by individual deviation. The only feasible deviation is to continue as a singleton. Since C is stand-alone stable no country can gain by leaving the coalition. Otherwise, if C is not a stable coalition structure and supported by any strategy profile, then if country j changes her announcement to $\{P_j\}$ the coalition structure turns into $C_i \backslash \{n_i\} \bigcup \{n_i - 1, 1\}$ and country j is better off due to (P.2) and $\pi(1; C_i) > \pi(n_i; C)$.
To obtain sharper predictions about stable coalition structures Yi and Shin (2000) introduce the equilibrium concept coalition-proof Nash equilibrium (CPNE)[16]. A Nash equilibrium is immune against individual deviations and a coalition-proof Nash equilibrium is immune against deviations which are self-enforcing and are not subject to further deviations. Coalition proofness imposes a consistency requirement on the game and rules out all non-credible threats [Finus and Rundshagen (2003)].
The following Lemma, proposed by Yi and Shin (2000), supports the understanding of the resulting equilibrium coalition structures.

Concerning the notation: $I(N/k)$ denotes the higher integer to N/k including N/k ($I(2.5) = I(3) = 3$) and $\{a_p, b_q, ..., h_w\} = \{a, ...a, b, ...b, h, ...h\}$ where there are p entries of a, q entries of b etc. [Yi and Shin (2000)].

Lemma 3. *$C = \{k_{m-1}, r\}$ is more concentrated than $C' = \{n_1, n_2, ..., n_{m'}\}$, where $m = I(N/k)$, $r = N - (m-1)k$, and $k \geq n_1 \geq ... \geq n_{m'}$.*[17]

Coalition structure $\{k_{m-1}, r\}$, where the number of research coalitions is given by $m = I(N/k)$ and $r = N - (m-1)k$, is the most concentrated

[14] For a definition of Nash equilibrium see Appendix A.
[15] For the detailed proof consult Yi and Shin (2000) Appendix A.
[16] See Appendix A for definition.
[17] The proof is provided in Appendix A of Yi and Shin (2000).

research coalition structure with the size of the largest coalition less than or equal to k. According to Yi and Shin (2000), following proposition states conditions which help to identify a coalition-proof Nash equilibrium:

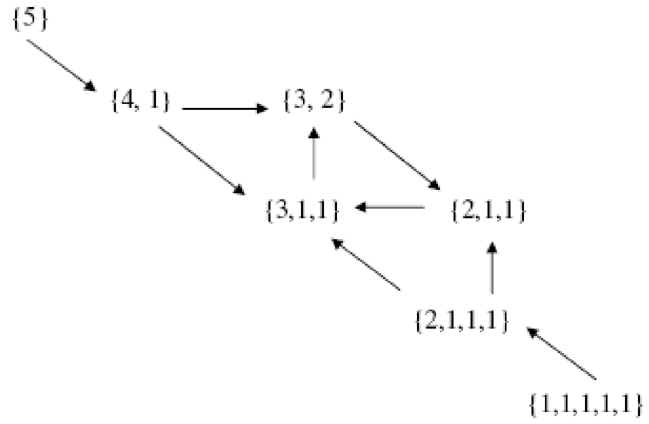
Proposition 3. *Suppose that $C^* \equiv \{k^*_{m^*-1}, r^*\}$ is stand alone stable, where $m^* = I(N/k^*)$ and $r^* = N - (m^* - 1)k^*$ with $1 \leq r \leq k^*$. The size-k coalition is not stand-alone stable in any research coalition structure for all $k = k^* + 1, ...N$. Then in the Exclusive Membership game:*

1. *C^* is the most concentrated Nash equilibrium coalition structure under (P.1)-(P.3).*
2. *C^* is a coalition-proof Nash equilibrium structure.*
3. *If there is any other coalition-proof Nash equilibrium coalition structure, it has exactly m^* research coalitions and is less concentrated than C^*.*
4. *If $r^* = k^* - 1$ or k^*, then C^* is the unique coalition-proof Nash equilibrium coalition structure.*

A detailed proof is conducted in Appendix A of Yi and Shin (2000) and a short demonstration of *(3)* is provided in Appendix B of this paper. Focusing on the intuition, Yi and Shin (2000) conclude that *(1)* is based on the hypothesis that no research coalition with the size of the largest research coalition greater than k^* is stand-alone stable. In any Nash equilibrium coalition structure the size of the largest research coalition is less than or equal to k^*.(2)indicates that C^* constitutes a CPNE because any deviation which creates a bigger coalition than k^* is not self-enforcing. The deviation would not constitute a Nash equilibrium among the deviators. Any other deviation is not profitable due to stand-alone stability and the conditions of the profit function (P.1)-(P.3).

Nevertheless, a size-k coalition with $k > k^*$ can emerge and be stand-alone stable such that a coalition-proof Nash equilibrium may fail to exist. Yi and Shin (2000) propose following example as to illustrate a situation when a coalition-proof Nash equilibrium may fail to exist in an Exclusive Membership game:

Example 1: An arrow pointing from one coalition structure C to another coalition structure C' implies that there is one member country which becomes better off by changing its membership to some coalition in structure C'.



$\{4,1\} \rightarrow \{3,2\}$ implies that $\pi(4;\{4,1\}) < \pi(2;\{3,2\})$. This example is in accordance with (P.1)-(P.3) but violates Proposition 2, because $C^* = \{2,2,1\}$ but $\{3,1,1\}$ is stand-alone stable: no coalition member has an incentive to play as a singleton. According to this concept there are four Nash equilibria: $\{3,1,1\}$, $\{2,2,1\}$,$\{2,1,1,1\}$ and $\{1,1,1,1,1\}$. From $\{2,2,1\}$,$\{2,1,1,1\}$ and $\{1,1,1,1,1\}$ three countries could make a profitable deviation to $\{3,1,1\}$. But even $\{3,1,1\}$ does not constitute a coalition-proof Nash equilibrium structure since the singletons could join together to induce $\{3,2\}$.
Yi and Shin (2000) introduce two additional conditions on the profit function to guarantee a well-defined equilibrium $C^* = \{k^*_{m^*-1}, r^*\}$ such that a size-k coalition with $k > k^*$ is not stand-alone stable. Since theses conditions play only a limited role they are introduced in the Appendix.

4.2.2 Open Membership Game

In this game each agent announces a list of agents they want to be in a coalition with. Agents who announce the same address are in the same coalition. Again, α^i is a country's announcement. Given all countries' announcements $\alpha \equiv (\alpha^1, \alpha^2, ..., \alpha^N)$, the resulting coalition structure is $C = \{D_1, D_2, ...D_m\}$ where country i and country j belong to the same coalition if, and only if, $\alpha^i = \alpha^j$. For example, there are four countries and $\alpha = (\alpha_1, \alpha_1, \alpha_4, \alpha_3)$, the resulting coalition structure is $C = \{2,1,1\}$ where country 1 and country 2 belong to the same coalition because they have chosen the same list and country 3 and 4 play as singleton. But in this case countries 3 and 4 can join country 1 and 2 by changing their announcement from α_3 or α_4 to α_1.

Since the consent of the coalitions members is not needed to be allowed to join the coalition stand-alone stability is a necessary condition for a coalition structure to be supported as a Nash equilibrium outcome. The existence of a Nash equilibrium structure is not guaranteed in this game unless the number of countries is small [Yi and Shin (2000)].

Proposition 4. *For $N \leq 4$ a NE coalition structure exists in the Open Membership game. Under (P.1)-(P.3) the most concentrated Nash equilibrium coalition structure is the unique coalition-proof Nash equilibrium structure.*

Yi and Shin (2000) provide a proof in Appendix A of their paper. Why a Nash equilibrium may fail to exist for $N \geq 5$ is explained by previously introduced Example 1. In this case no research coalition structure can be supported as a Nash equilibrium because there is always one country who becomes better off by leaving and to join another country or to play as singleton. In this case there arises a circle among $\{3, 2\}$, $\{3, 1, 1\}$ and $\{2, 2, 1\}$. Similar to the additional conditions in Appendix B, Yi and Shin (2000) introduce a fourth condition on the profit function to prevent this circle. (P.4), which, along with conditions (P.1)-(P.3), guarantees a unique coalition-proof Nash equilibrium in the open membership game.

- (P.4) $C = \{n_1, ...n_m\}$ is stand-alone stable. If $n_1 \geq n_m + 2$, then there exists a n_j, $n_1 \geq n_j + 2$, such that $\pi(n_1; C) < \pi(n_j + 1; C')$, where $C' = C\{n_1, n_j\} \cup \{n_1 - 1, n_j + 1\}$. If the size of the largest research coalition exceeds the size of the smallest research coalition by 2 or more members, a member of the largest research coalition becomes better off by joining one of the smaller coalitions [Yi and Shin (2000)].

This conditions implies the emergence of a rather symmetric coalition structure.

Lemma 4. *(P.4) holds in the linear quadratic model of R&D competition*[18] *for $\beta > 1/2$ and $b\gamma \geq 2$.*

(P.4) also reflects the free-riding problem in coalition formation with positive externalities. A member of a larger coalition conducts more research. The country decreases her research expenditure and reduces the contribution to thw public good research by joining a smaller coalition. However, even

[18]The proof of Lemma 4 is depicted in Yi and Shin (2000) Appendix B.

though (P.4) is necessary to generate an equilibrium in this game, Yi and Shin (2000) acknowledge one drawback: (P.4) is not yet compatible with the linear-quadratic Cournot model since Assumption 1 is violated. The aggregate payoff $V(x_i, X)$ is lower under C' than under C and reduces the deviators payoff by holding the investment constant [Yi and Shin (2000)]. Finally, Proposition 4 has been established to introduce the coalition-proof Nash equilibrium under conditions (P.1)-(P.4).

Proposition 5. *Suppose that* $C^{**} \equiv \{k^{**}_{m^{**}-q^{**}}, k-1^{**}_{q^{**}}\}$ *is stand-alone stable, where* $k^{**} = I(N/m^{**})$ *and* $q^{**} = m^{**}k^{**} - N(\geq 0)$. *Suppose that* $k_{m-q}, k-1_q$ *is not stand-alone stable, where* $k = I(N/m)$ *and* $q = mk/N$, *for all* $m = 1, ...m^{**} - 1$. *Then in the open membership game:*

1. *Under (P.4),* C^{**} *is the most concentrated Nash equilibrium coalition structure and*

2. *Under* $(P.1)-(P.4)$, C^{**} *is the unique Nash equilibrium coalition structure.*[19]

Yi and Shin (2000) conclude that for $C = \{n_1, ..., n_m\}$, $n_1 \geq ... \geq n_m$ to be a Nash equilibrium coalition structure in the Open Membership game under (P.4), it must be that $n_1 \leq n_m + 1$ so that $C = \{k_{m-q}, k-1_q\}$ where $k = I(N/m)$, $q = mk - N$. $\{k_{m-q}, k-1_q\}$ is clearly more concentrated than $\{k_{m'-q'}, k'-1_{q'}\}$ where $m < m'$. C^{**} is the most concentrated stand-alone stable coalition structure among N symmetric coalition structures $C = \{k_{m-q}, k-1_q\}$, $m = 1, ..., N$, where $k = I(N/m)$ and $q = mk/N$. This yields $\{N\}$,$\{N/2, N/2\}$, $\{N/3, N/3, N/3\}$, $\{N/4, N/4, N/4, N/4\}$,..., $\{2, 2, ..., 2\}$, $\{2, 2, ..., 1, 1\}$, ...$\{2, 1, ..., 1, 1\}$, and finally $\{1, 1, ..., 1, 1\}$. To show that *(2)* holds Yi and Shin (2000) conclude that it is similar to Proposition 2. A group deviation to create a larger coalition is not feasible by (P.4) or by stand-alone stability.

4.2.3 Socially Optimal Coalition Structure

Proposition 6. *The grand coalition is the socially efficient coalition structure under Assumption 1 and 2.*

The entire aggregate payoff is higher under the grand coalition than under any other coalition structure. The grand coalition maximizes the entire

[19] The detailed Proof is provided in the Appendix A of Yi and Shin (2000).

aggregate payoff and consumer surplus is highest under Assumption 5 [Yi and Shin (2000)].

4.2.4 Evaluation

To accomplish a comparison of the two games, consider that $\{k_{m-1}, r\}$ denotes the most concentrated coalition structure with the largest coalition equal to k; and $\{k_{m-q}, k/1_q\}$ is the least concentrated coalition structure with m coalitions. By Proposition 2, a stand-alone stable coalition structure $C^* \equiv \{k^*_{m^*-1}, r^*\}$ is the most concentrated Nash equilibrium and the unique coalition-proof Nash equilibrium whenever $r^* = k^* - 1$ or k^*. By Proposition 4, on the Open Membership game coalition structure $C^* \equiv \{k^{**}_{m^{**}-q^{**}}, k{-}1^{**}_{q^{**}}\}$ is the most concentrated stand-alone stable coalition structure.
This leads Yi and Shin (2000) to the conclusion that:

- Under Proposition 2 any Nash equilibrium coalition structure of the Open Membership game, if one exists, is (weakly) less concentrated than the most concentrated Nash equilibrium coalition structure of the Exclusive Membership game.

- Under (P.1)-(P.3) and the conditions of Proposition 3, any coalition-proof Nash equilibrium coalition structure is less concentrated than the most concentrated coalition proof Nash equilibrium coalition structure of the Exclusive Membership Game.

For both statements it is necessary to consider that stand-alone stability is a necessary condition for a Nash equilibrium to exist at all. According to Proposition 3, the equilibrium coalition structure C^* is more concentrated than any other equilibrium structure with the larger coalition of less or equal size k^*.
Further, Yi and Shin (2000) conclude that:

- Under (P.1)-(P.4) and the conditions of Proposition 2 and 4, the unique coalition-proof Nash equilibrium coalition structure of the Open Membership game is (weakly) less concentrated than any coalition-proof Nash equilibrium coalition structure of the Exclusive Membership game.

This can be deducted from the fact that $C' = \{k'_{m^*-q'}, k' - 1_{q'^*}\}$, where $k' = I(N/m^*)$ and $q' = m^*k' - N$ is less concentrated than any research coalition

structure with m^* coalitions; and, under (P.4), C' is the only candidate for a Nash equilibrium structure with m^* coalitions in the open membership game. Yi and Shin (2000) show that all in all the exclusive membership rule supports a more concentrated coalition structure as a stable outcome than the open membership rule does. Under condition (P.3) members of a small size-r^* coalition in C^* earn lower profits if they admit a new member from the size-k^*. Under assumption (P.4) a member of the size-k^* coalition wants to join the smaller coalition (this is unless $r^* = k^* - 1$ or k^* so that C^* and C^{**} coincide) and cannot be denied access due to open membership. Thus, the more concentrated C^* cannot be sustained as a Nash equilibrium outcome of the open membership game under (P.4), unless $r^* = k^* - 1$ or k^* so that C^* and C^{**} coincide.
Exclusivity of membership allows some countries to form smaller coalitions and thereby inducing other countries to form a larger coalition and provide more of the public good. This result supports Poyago-Theotoky's (1995) definition of an 'entry-blocking' coalition.
On the other hand, the Open Membership rule equalizes the coalition sizes as the members of smaller coalitions cannot block entry.

In accordance with the linear-quadratic Cournot model and conditions (P.1)-(P.4) of the profit function Yi and Shin (2000) establish two simulation for the Open and Exclusive Membership game for $N = 1$ to $N = 9$ participants and $\beta = 0.6, 0.8$ and 1. Table 2 and 3 illustrate the above stated results and show that the grand coalition is not an equilibrium outcome for $N \geq 5$ for all β and for neither of the games. High positive externalities invite free-riders to undermine the coalition's effort. Yi and Shin (2000) conclude that even without assumptions (P.1)-(P.3) the existence of a Nash equilibrium coalition structure is guaranteed in the Exclusive Membership game. For the linear-quadratic Cournot model, Table 2 lists the coalition-proof Nash equilibrium coalition structures of the Exclusive Membership game. Due to exclusivity of membership there are many Nash equilibrium coalition structures; coalition structures which are stand-alone stable. For example for $N = 6$ and $\beta = 1$ there are nine Nash equilibrium structures: $\{4, 2\}$, $\{4, 1, 1\}$, $\{3, 3\}$, $\{3, 2, 1\}$, $\{3, 1, 1, 1\}$, $\{2, 2\}$, $\{2, 2, 1, 1\}$, $\{1, 1, 1, 1, 1\}$. Further Yi and Shin (2000) conclude that as the spillover rate increases, a more concentrated coalition structure becomes stand-alone stable and a Nash equilibrium or coalition-proof Nash equilibrium outcome in both games. A higher spillover rate eliminates the underinvestment problem in a situation of non-

	β = 0.6	β = 0.8	β = 1
N=2	{1, 1}, {2}*	{1, 1}, {2}*	{1, 1}, { 2}*
N=3	{1, 1, 1}, {2, 1}, {3}*	{1, 1, 1}, {2, 1}, {3}*	{1, 1, 1}, {2, 1}, {3}*
N=4	{1, 1, 1, 1}, {2, 1, 1}, {2, 2}*, {3, 1}*	{1, 1, 1, 1}, {2, 1, 1}, {2, 2}*, {3, 1}*	{1, 1, 1, 1}, {2, 1, 1}, {2, 2}, {3, 1}, {4}*
N=5	all *C* with 3; {3, 2}*	all *C* with 3; {3, 2}*	all *C* with 3; {3, 2}*
N=6	all *C* with 3; {3, 3}*	all *C* with 3; {3, 3}*	all *C* with 4; {3, 3}*, {4, 2}*
N=7	all *C* with 3; {3, 2, 2}*, {3, 3, 1}*	all *C* with 3; {3, 2, 2}*, {3, 3, 1}*	all *C* with 4; {4, 3}*
N=8	all *C* with 3; {3, 3, 2}*	all *C* with 3; {3, 3, 2}*	all *C* with 4; {4, 4}*
N=9	all *C* with 3; {3, 3, 3}*	all *C* with 3; {3, 3, 3}*	all *C* with 3; {4, 4, 1}*

Table 2: Coalition-proof Nash equilibrium structure under Exclusive Membership rule. A coalition structure with * is a coalition-proof NE coalition structure. 'all C with k' means all coalition structures with the size of the largest research coalition less than or equal to k [compare Yi and Shin (2000)].

	β = 0.6	β = 0.8	β = 1
N=2	{2}*	{2}*	{2}*
N=3	{3}*	{3}*	{3}*
N=4	{2, 2}*	{2, 2}*	{2, 2}, {4}*
N=5	{3, 2}*	{3, 2}*	{3, 2}*
N=6	{2, 2, 2}, {3, 3}*	{2, 2, 2}, {3, 3}*	{2, 2, 2}, {3, 3}*
N=7	{3, 2, 2}*	{3, 2, 2}*	{3, 2, 2}, {4, 3}*
N=8	{2, 2, 2, 2}, {3, 3, 2}*	{2, 2, 2, 2}*, {3, 3, 2}*	{2, 2, 2, 2}, {3, 3, 2}, {4, 4}*
N=9	{3, 2, 2, 2}, {3, 3, 3}*	{3, 2, 2, 2}, {3, 3, 3}*	{3, 2, 2, 2}, {3, 3, 3}*

Table 3: Open Membership game: Nash equilibrium and coalition-proof Nash equilibrium under open Membership Rule [compare Yi and Shin (2000)].

cooperation and increases the private gains from forming research coalitions. This supports the conclusion of Poyago-Theotoky (1995), who equally derives the result that high strategic complements provide the possibility of high participation.

Given that R&D investment increases with concentration, following statement can be derived with regards to global welfare:

Proposition 7. *Under Assumption 1-3, the Exclusive Membership rule leads to higher industry R&D investment and thus higher consumer surplus than the Open Membership rule does.*

Yi and Shin (2000) add that for an analytical proof the effects of (P.4) and (P.3) are conflicting. Whenever one member deviates to a larger or equal size coalition, the deviator is worse off and the remaining members are better off. Nevertheless, their simulation results of the linear-quadratic Cournot model confirm above proposition.

5 Summary and Conclusion

The motivation for this paper was to highlight the benefits of research cooperation as well as to depict the influence and drawbacks of changing spillover rates. Firstly, I introduced the well known linear-quadratic, 2-stage Cournot model to illustrate the effects of an increasing spillover rate on research output and size of the resulting coalition. Poyago-Theotoky (1995) assumes that coalition members can internalize the fruits of their research by entirely sharing their data and information in order to take better decisions and introduce better policies. In contrast, the spillover rate from the coalition members to the non-members varies between 0 and 1. Thus, the achieved cost reduction and R&D output of coalition members will always exceed the output of non-members and also outweighs the situation where no cooperation takes place. A low spillover rate, strategic substitutes, to non-members decreases their competitiveness. In this case coalition members gain higher individual profits than in the presence of high spillovers. Consequently, full cooperation is hardly possible because coalition members are unwilling to open up their coalition to a less productive agents in apprehension that the average payoff will decrease. When spillovers take the form of strategic complements and are close to one, the competitiveness of outsiders does not lag behind significantly and a higher level of cooperation and eventually even full cooperation is possible. From a social welfare point of view, this development is desirable since the socially optimal payoff can only be achieved by the grand coalition. The increasing spillover rate reflects the trade off between a high individual payoff and low social payoff on the one hand (when the spillover rate is low), and broad participation, high social payoff but relativley small individual payoff on the other hand (when the spillover rate is high). Full cooperation is only an equilibrium outcome when $\beta = 1$.
According to this reasoning Poyago-Theotoky (1995) concludes that for any spillover rate $\beta < 1$ the size of the coalition settles at $k \leq n$; research coalitions are of entry blocking type and refuse membership to less productive

countries. To achieve a higher level of cooperation a system of incentives has to be set up to compensate the initial coalition members for allowing more countries to join the coalition or for increasing the spillover rate to one or close to one. Subsidies could be an option to compensate members of the equilibrium size coalition for the expansion of the coalition or the increasing spillover rate and to increase the private gains of coalition members. Equally it can be concluded that GEOSS needs some pioneering countries, which increase their spillover rate to a higher level to trigger the dynamics of coalition formation and eventually reach full cooperation.

On the basis of the model of Carraro and Siniscalco (1995, 1997), linkage of negotiations can be proposed as compensation mechanism for the incurred costs of expanding the coalition. This additional agreement could take the form of a trade agreement, which allows the counries to generate extra benefits.

Another proposition, which has been introduced in the second part of this discussion paper, was to change the rules of coalition formation and advocate the formation of multiple coalitions instead of only one partial coalition. Since GEOSS is composed of 42 tasks, which develop and provide monitoring systems,model and data and therefore constitute the System of Systems, the member countries are participating organisations are already grouped by interest. However, the results show that even then, full cooperation is hard to achieve. But it might be possible that by allowing the formation of several small coalitions, or tasks, more agents can be engaged to contribute to GEOSS. These concerns have been investigated by Yi and Shin (2000). They transform the linear-quadratic Cournot club good model to a linear-quadratic public good model which displays a homogenous spillover rate for coalition members as well as outsiders. Whereas Poyago-Theotoky (1995) applies varying spillover rates and speaks of an entry blocking coalition, Yi and Shin (2000) assume that non-members refuse to join the coalition because they are better off as free-riders. Yi and Shin (2000) assume a high spillover rate, with an inter-coalition spillover rate equal or nearly equal to the intra-coalition spillover rate and describe a situation when strategic complements are at work. Freely interpreted this implies that the individual payoffs are influenced by the sum of implemented policies and decisions and not by the composition of other countries research, which is reflected in the size and form of spillovers. Smaller coalitions implement fewer policies and incurr fewer costs but still internalise the gains of the higher research effort and policies of the larger coalitions. Yi and Shin (2000) introduce a set of conditions on the payoff function and introduce two games with either Exclusive or Open Membership rule. Neither of the games achieves a grand coalition for $N \geq 5$ due to high free-riding incentives. The Open Membership game,- all agents can join whichever coalition they like, leads to a rather symmetric coalition structure. Freely interpreted, this could imply that rather diversified coalitions with heterogenous agents emerge. In contrast, in the Exclusive Membership game coalitions are allowed to restrict membership, which allows them to select agents according to similar needs and ressources, for example agents who have to fight problems of desertification, or possess and manage rain forest areas. This practice allows them to concentrate their research and avoid the scattering of results by a less specialised country.

Even though these results are instructive for the design of future research agreements, they have to be interpreted with caution due to the simplified framework. The results of this discussion paper suggest that participation to GEOSS could be increased by (i) intervening in the coalition formation process and changing the rules of the formation process (e.g. by restricting membership to certain coalitions to a set of agents), (ii) offering compensations for the coalition members which contribute to the public good (e.g. offering an adequate cost recovery system), or (iii) linking GEOSS to an external agreement which allows members to generate additional benefits. These measures require the intervention of an external, coordinating institution with enforcement or sanctioning powers. This is not the case since participation to GEOSS is voluntary and non-legally binding. Consequently, full participtaion to GEOSS depends on the willingness of a set of pioneering countries and organisations who fully engage in the negotiations and release their data and information. These agents are aware of the fact that their effort and trust can contribute to greater social welfare.

6 APPENDIX

A Equilibrium Concepts

To define an equilibrium coalition structure, Finus and Rundshagen (2003) introduce two well known equilibrium concepts: Nash equilibrium and the coalition-proof Nash equilibrium.

Definition 5. *Nash Equilibrium Coalition Structure:*
Let $G = \{P, \sum = \{\sum_i\}_{i \in P}, \overline{\pi}(C(\sigma)) = \{\pi(n_i; C)\}_{i \in P}\}$ *be the first stage of the coalition formation game with countries* $i \in P$*, strategy vectors* $\sigma \in \sum$*, which resembles a proposal for a coalition, the resulting coalition structure* C *and vectors of payoff function* $\overline{\pi}$*. Let* $\widetilde{\boldsymbol{C}}(n^S, \sigma)$ *be the set of coalition structure that a subgroup of countries* n^S *can induce if the remaining countries* $j \in P \backslash n^S$ *play* σ_j*. For a fixed strategy vector* σ *defines the reduced game for a subgroup* n^S *as* $G^S_\sigma = \{n^S, \{\sum_i\}_{i \in n^S}, \{\pi(\widetilde{n}_i; \widetilde{\boldsymbol{C}}(n^S, \sigma)\}_{i \in n^S}\}$.
Then σ^* *is called a Nash equilibrium (NE) with the resulting Nash equilibrium coalition structure* C^* *if no singleton* $n^S = \{i\}$ *can increase her payoff by inducing another coalition structure:*

$$C^*(\sigma^*) \textit{ is a NE if } \forall\, i \in P \textit{ and } \forall \widetilde{C} \in \widetilde{\boldsymbol{C}}(\{i\}, \sigma^*) : \pi(n_i; C^*) \geq \pi(\widetilde{n}_i; \widetilde{C})$$

A NE requires that a coalition structure is immune to deviations by single countries. A stand-alone stable coalition structure constitutes a NE coalition structure. Finus and Rundshagen (2003) have established following definition for coalition-proof Nash equilibrium coalition structure helps to obtain sharper predictions on equilibrium coalition structures. Coalition-proofness rules out non-credible deviations, such that a coalition structure can only be challenged by self-enforcing deviations. Coalition-proofness considers deviations of subgroups of countries but also includes the special case of deviations by singletons, such that a CPNE can be considered as subset of NE.

Definition 6. *Coalition-proof Nash equilibrium Coalition Structure:*
For $P = \{1\}$ α_i *is a coalition-proof Nash equilibrium if, and only if, it is a Nash equilibrium. Assuming that* $|P| = n > 1$ *and that coalition-proof Nash equilibrium coalition structures have been defined for all* $m < n$*. Then:*
α *is self-enforcing if, and only if, for all* $n^S \subset P$*,* $n^S \neq I$*,* α_{n^S} *is a coalition proof Nash equilibrium of* G^S_α
α^* *is a coalition proof Nash equilibrium of* G *with the coalition-proof coalition*

structure C^* if, and only if, it is self-enforcing and there does not exist another self-enforcing strategy α' such that $\pi(n_i(\alpha'); C(\alpha')) \geq \pi(n_i^*, C^*) \forall i \in P$ and $\pi(n_i(\alpha'), C(\alpha')) > \pi(n_i^*, C^*)$ for at least one i

B Coalition Formation

Exclusive Membership Game

To show that the equilibrium of the exclusive membership game can be well-defined Yi and Shin (2000) introduce two additional conditions; the detailed proof can be found in Yi and Shin (2000) Appendix A.

- (P.5) $C = \{n_1, ...n_m\}$, $C' = C\backslash\{n_i, n_j\} \in \{n_i - 1, n_j + 1\}$, $\hat{C} = C\backslash\{n_k, n_l\} \in \{n_k + n_l\}$, and $\hat{C}' = \hat{C}\backslash\{n_i, n_j\} \in \{n_i - 1, n_j + 1\}$, where $n_1 \geq ... \geq n_m$ and $n_i \geq n_j + 2$. Then $\pi(n_k + n_l; \hat{C})/\pi(n_k; C) > \pi(n_k + n_l; \hat{C}')/\pi(n_k; C')$.

A change in the coalition structure which increases concentration increases profitability of the merger of coalition s not involved in the change of the coalition structure.

- (P.6) $C = \{n_1, ...n_m\}$ and $C_i = C\backslash\{n_i\} \in \{n_i - 1, 1\}$, $n_1 \geq ... \geq n_m$, $i = 1, ..., m$. If $\pi(n - 1; C) \geq \pi(n_1; C_1) \geq \pi(1; C_1)$, then $\pi(n_i; C) \geq \pi(1; C_i)$ for all $i = 2, ..., m$.

If the largest coalition is stand-alone stable, then all other coalitions in the coalition structure are stand-alone stable.

To demonstrate point *(3)* of Proposition 2 Yi and Shin (2000) assume a coalition structure with more and smaller or equal sized coalitions, which constitutes a Nash equilibrium coalition structure: $C = \{n_1, n_2, ..., n_m\}$ with $k^* \geq n_1 \geq ... \geq n_m$, $m > m^*$ and i^* such that $\sum_{j=i^*}^m n_j \geq r^* > \sum_{j=1^*+1}^m n_j$; and show that all countries can engage in a profitable and self-enforcing group deviation to $C^* \equiv \{k^*_{m^*-1}, r^*\}$. The last r^* countries are better off because $\pi(r^*; C^*) \geq \pi(1; C_r^*) \geq \pi(n_m; C) \geq \pi(n_j; C)$, $j = i^*, ..., m$ and $C_r^* = \{C^*\backslash\{r^*\} \cup \{r^* - 1, 1\} = \{k^*_{m^*-1}, r^* - 1, 1\}$. The first inequality follows from stand-alone stability of C^*; the second inequality from (P.1)-(P.3); the third inequality follows (P.2) which states that or small coalitions always earn a higher payoff than the coalition members. The $(m^*-1)k^*$ countries are better off because $\pi(k^*;C) \geq \pi(1;C_k^*) \geq \pi(1;C^* - k4) \geq \pi(n_{i^*};C) \geq \pi(n_j;C)$ where $j = 1,...,i^* - 1$ and $C_k^* = C^*\backslash\{k^*\} \cup \{k^* -, 1\} = \{k^*_{m^*-2}, k^* - 1, 1, r^*\}$ and $C_{k4}^* = C_k^*\backslash\{r^*\} \cup \{r^* - \sum_{j=i^*+1}^{m} n_j, n_{i^*+1}, ..., n_m\}$, which is less concentrated than C_k^*. The first inequality follows again from stand-alone stability of C^*; the second inequality from (P.1), because if a coalition structure becomes more concentrated countries who are not involved in the change of the coalition structure and remain free-riders earn higher payoffs; the third inequality follows from (P.1)-(P.3); and the fourth inequality follows (P.2). C^* Pareto dominates C and all countries can make a profitable and self-enforcing deviation to C^*. Yi and Shin (2000) conclude that if there exists any other coalition-proof Nash equilibrium coalition structure, it must have exactly m^* research coalitions.

References

[1] Jeremy Bulow, John Geanakoplos, and Paul Klemperer. Multimarket oligopoly: Strategic substitutes and complements. *The Journal of Political Economy*, Vol. 93, No. 3.:488–511, 1985.

[2] Carlo Carraro and Carmen Marchiori. Endogenous strategic issue linkage in international negotiations. *Working Paper No. 40.2003; FEEM-Fondazione Eni Enrico Mattei, CTN- Coalition Theory Network; Italy; www.feem.it*, 2003.

[3] Carlo Carraro and Domenico Siniscalco. Policy coordination for sustainability: Committments transfers and linked negotiations. *In: Goldin, I. and Winters, L.A., ed.: The Economic of Sustainable Development.*, Cambridge Univesity Press, Cambridge:264–282, 1995.

[4] Carlo Carraro and Domenico Siniscalco. R&d cooperation and the stability of international environmental agreements. *In: Carraro, C., ed.: International Environmental Negotiations: Strategic Policy Issues.*, E. Elgar, Cheltenham:71–96, 1997.

[5] Bruno Cassiman. Research joint ventures and optimal r&d policy with asymmetric information. *International Journal of Industrial Organization*, 18:283–314, 2000.

[6] Herman Cesar and Aart de Zeeuw. Issue linkage in global environmental problems. *In: Xepapadeas, A., ed.: Economic Policy for the Environment and Natural Ressources.*, E. Elgar, Cheltenham:158–173, 1996.

[7] Claude D'Aspremont, Alexis Jaquemin, Jean Jaskold Gabszewicz, and John A Weyman. On the stability of collusive price-leadership. *Canadian Journal of Economics*, 16:17–25, 1983.

[8] Michael Finus. Stability and design of international environmental agreements: The case of transboundary pollution. *In: Folmer, H. and Tietenberg, T.; ed.: International Yearbook of Environmental and Resource Economics, 2003/4*, E. Elgar, Cheltenham:82158., 2003.

[9] Michael Finus and Bianca Rundshagen. Endogenous coalition formation in global pollution control: a partition function approach. In *Carraro,*

C., ed.: The Endogenous Formation of Economic Coalitions. E. Elgar, Cheltenham, pages 199–243, 2003.

[10] Sergiu Hart and Mordecai Kurz. The endogenous formation of coalitions. *Econometrica*, 51:1047–64, 1983.

[11] Julie Newton. Wellbeing and the naturtal environment: A brief overview of the evidence; 2007; wellbeing in developing countries (wed) research group; university of bath.

[12] Joanna Poayago-Theotoky. Equilibrium and optimal size of research joint venture in an oligopoly with spillovers. *The Journal of Industrial Economics*, 43, No. 2:209–226, 1995.

[13] Sang-Seung Yi. Endogenous formation of economic coalitions. a survey of the partition function approach. In *Carraro, C., ed.: The Endogenous Formation of Economic Coalitions. E. Elgar, Cheltenham*, pages 80–127, 2003.

[14] Sang-Seung Yi and Hyukseung Shin. Endogenous formation of research coalition with spillovers. *International Journal of Industrial Organization*, 18:229–56, 2000.

Global interdependencies between population, water, food, and environmental policies

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Global interdependencies between population, water, food, and environmental policies

Abstract

Food and water resources are pressured by a growing human population which also becomes richer. More food will be demanded from less land and water. This study uses a global, partial equilibrium, integrated bottom-up modelling approach of the agricultural and forest sectors to quantify the relationship between food and water scarcity for different development pathways. The key questions addressed are: 1) How do agricultural producers adapt crop management intensities related to irrigation under increasing demand for food, increasing water scarcity, and environmental policies? 2) How does development affect food prices, food security, and the share of animal sources in human diets in different regions?

To answer the above questions, we integrate major crops with management intensity alternatives; livestock production, forest management, and dedicated energy plantations. The optimization model maximizes economic surplus subject to technological, water, land, and policy constraints. Global international market adjustments are portrayed through eleven regions with endogenous commodity price and trade levels.

Keywords

land use economics; resource scarcity; irrigation; water; environmental policy; food security; population growth; income development; agricultural sector; forestry; bioenergy; greenhouse gas emission mitigation; mathematical programming; integrated assessment; bottom-up analysis; partial equilibrium; welfare maximization; FASOM model

Classifications

105.000 ENVIRONMENTAL PROBLEMS AND ISSUES – Land-use change;
107.200 ENVIRONMENTAL PROBLEMS AND ISSUES – Water scarcity;
205.000 BIOSPHERES AND ECOSYSTEM – Forests;
308.000 DISCIPLINE – Agriculture;
309.000 DISCIPLINE – Forestry;
404.000 MANAGEMENT OF THE ENVIRONMENT – Management and regulation;
406.000 MANAGEMENT OF THE ENVIRONMENT – Policy analysis;
500.000 HUMAN-BASED FIELDS WITHIN ENVIRONMENTAL SCIENCE;
602.000 TOOLS FOR ENVIRONMENTAL RESEARCH AND MANAGEMENT – Modelling;
603.000 TOOLS FOR ENVIRONMENTAL RESEARCH AND MANAGEMENT – Statistics/mathematical analysis;
701.000 COUNTRIES AND GEOGRAPHICAL REGIONS – General/global

Global interdependencies between population, water, food, and environmental policies

Food, land, and water constitute three of the most fundamental resources for mankind. These resources are under pressure by population growth and global change. Essentially, more food may need to be produced with less resources of land and water. Resource scarcity is not a new phenomenon in human history. Growing populations in the past have caused local over exploitation of natural resources leading to the extinction or collapse of several ancient societies (Diamond 2005). However, today's resource scarcity is not only an acute problem in isolated locations but it is also a global threat. Several arguments can illustrate the global dimension of this threat. First, the collective use of resources for food production over all countries has reached substantial proportions. In 2005, agriculture occupied about 38 percent of the global land area (FAOSTAT 2005) yielding an average agricultural land use of 0.77 hectare per capita. Without technical progress and agricultural intensification and with current rates of population growth, agriculture would need an area equivalent to 1/2 and 2/3 of the current terrestrial land area by 2030 and 2070, respectively, in order to maintain current food consumption levels per capita. Similar calculations could be made with respect to fresh water and energy resources.

The second argument is that although some regions experience more challenges than others, today's societies are increasingly connected. Globalization opens the door to more international trade. Thus, regional commodity supply shortage or surplus can be transferred to and mitigated by world markets. Furthermore, globalization has reached governments. Since the establishment of the United Nations in 1945, many different international treaties have been adopted, which may particularly affect global food production and distribution. Environmental treaties relevant to food production include the convention on wetlands (RAMSAR convention), the Climate Change convention, and the convention on biological diversity (CBD convention). These treaties may limit possible expansion of agricultural land. However, expansion of land might be desirable to fulfill the eight millennium development goals defined by the world leaders at the United Nations Millennium Summit in 2002 since they include targets for the reduction of hunger and malnutrition. A third argument is that the cumulative impacts of local land use decisions may cause significant global environmental feedback, foremost through climate change. There are both positive and negative agricultural impacts which influence the availability and fertility of land, the length of growing season, fresh water endowments, pest occurrence, CO_2-fertilization, and the frequency of extreme events related to draughts, flooding, fire, and frost.

Although global commodity trade and environmental policies are important drivers, a variety of additional factors influence the net impact of future development on land use and food supply. These factors include technical progress, land use intensities, land quality variations, resource endowments, and food demand characteristics. Technical progress and management intensification can reduce land and water scarcity. While improved technologies shift the production possibility frontier outwards, intensification moves production along a frontier by substituting one resource with another. Intensification is often related to land but could be related to any other resource. A more intensive land use, for example, can be achieved by employing more water, fertilizer, pesticides, machinery, or labor. Note that intensification of water and land can work in different directions. If all other resources except land and water are kept constant, land intensification will relax land scarcity but increase water scarcity. However, if intensification involves increased use of other resources such as fertilizer and labor, both land and water scarcity may be relaxed.

The variation of land quality also interacts with development. On the one hand, population growth increases food demand and in turn the demand for agricultural land. Since rationally acting agents use the most suitable resource first, additional agricultural land is likely to be less productive. On the other hand, population growth increases predominantly urban land areas (United Nations 2004). This expansion potentially removes high quality agricultural areas since cities are usually built on fertile land. Furthermore, increased agricultural intensity due to population growth may increase land degradation over time. This could trigger a positive feedback loop where increased degradation leads to more degradation through intensification. Fourth, income growth especially in low income regions raises demand for animal based food more than demand for vegetarian food. Since animal food production involves an additional element in the food chain, it may increase land requirements per calorie by a factor of 10 or more relative to vegetarian food (Gerbens-Leenes and Nonhebel 2005). Thus, an increased demand of animal food is likely to increase total agricultural land use and management intensities with the above described implications.

Sustainable development is a frequently declared objective of national and multinational governments. Land use has a crucial impact on sustainability because it links the essential resources food, water, climate, soils, and wildlife. To maximize the social benefits from land use, governmental interference is necessary to internalize social costs of land use externalities (Cowie et al. 2007). However, efficient policy design requires an accurate understanding of the complex, and heterogeneous, and discontinuous interdependencies of land use. This study presents and applies a tool that can be used to assess alternative development scenarios. In contrast to previous studies, we combine detailed geographical modeling of land qualities with multiple market and non-market impacts from land use at the global level.

The remainder of the paper is organized as follows: the next two sections briefly describe the global land use model and its data. Section 4 explains the scenarios. Section 5 discusses the simulation results and section 6 concludes.

A global integrated land use optimization model

To assess interdependencies between population growth, economic and technological development, and the associated scarcity of land and water, we use a mathematical programming based model of the agricultural and forest sectors. Concept and structure of this model are similar to the US Agricultural Sector and Mitigation of Greenhouse Gas (ASMGHG) model (Schneider, McCarl and Schmid 2007). The model integrates geographic explicit information about land qualities and technologies to portray the heterogeneity of farming conditions. Particularly, land qualities are represented by up to 5 altitude, 6 soil, and 7 slope classes. Technological options involve choices between 46 crops, 59 agricultural, forest, and bioenergy products; and up to 5 irrigation, 2 tillage, and 3 fertilization alternatives. More than 20 environmental impacts include soil carbon sequestration, nutrient run off and percolation, soil erosion, deforestation, and greenhouse gas accounts related to bioenergy and animal husbandry.

Global agricultural and forest product markets are represented by 11 regions[7]. Every region can trade commodities with every other region subject to transportation costs and tariffs, export subsidies, quotas where they apply. The model accounts for the annual net trade between regions. Demand is specified as horizontal, linear, constant elasticity, or vertical function. However, for the majority of commodities, downward sloping demand functions with constant elasticities are adopted. Horizontal functions are used for commodities, of which the price is insensitive to agricultural decisions. Vertical demand functions represent political targets, i.e. on bioenergy. Supply functions are explicitly specified for the resources land, water, and irrigated land, and for forest products. Endogenous variables include crop, livestock, forest, and bioenergy production activities; commodity use and trade, aggregate welfare measures, and environmental impacts. The global agricultural and forest market equilibrium is computed by choosing land use activities as to maximize the sum of producer and consumer surplus subject to resource, technological, and political restrictions. Development is simulated by adjusting key exogenous model parameters related to commodity demand, resource endowments, technologies, and policies. These adjustments are described in the section four on scenarios.

When uncalibrated, large-scale land use optimization models are solved for the base period, they do not usually reproduce observed decisions. There are a variety of reasons for deviations. First, some data which influence land use decisions are difficult or impossible to obtain. For example, the impacts of crop rotations on yields, costs, labor, and machinery are not available beyond a number of individual case studies. Second, some data are inaccurate because of measurement errors, inconsistent data collection methods, or insufficient resolution of the data. Third, our model operates at the sector level and does not explicitly portray many farm specific details, commodity qualities, and other local differences. Fourth, we assume competitive markets and rational behavior. To bring base solutions close to observation, we calibrate the direct costs for land management alternatives. Following classical economic theory, we adjust the cost of

[7] A version with 33 regions is currently in the testing phase.

management options such that at base prices, marginal revenues equal marginal costs (Wiborg et al. 2005).

Our modeling approach can be put in perspective with alternative methods. Previous land use assessments may be distinguished regarding a) the flow of information in top-down and bottom-up systems, b) the dominating analysis technique in engineering, econometric, and optimization approaches, c) the system dynamics in static equilibrium, recursive dynamic, and fully dynamic designs, d) the spatial scope in farm level, regional, national, multi-national, and global representations, and e) the sectoral scope in agricultural, forestry, multi-sector, full economy, and coupled economic and environmental models. Additional differences involve various modeling assumptions about market structure and the applied resolution over space, time, technologies, commodities, resources, and environmental impacts and associated data. For a more detailed survey over specific land use models, we refer to Lambin et al. (2000), Heistermann et al. (2006) and van der Werf and Peterson (2007).

Applying classifications a) to e), the model used in this study characterizes as bottom-up, optimization (welfare maximization), static equilibrium, global, agricultural and forest sector model. In addition, it portrays environmental relationships and global agricultural and forestry commodity trade.

Data

A global, bottom-up land use model is by definition data intensive. In mathematical terms, these data consist of objective function coefficients, technical coefficients, and right-hand side values. Conceptually, these data identify demand and supply function parameters, transportation costs, policy parameters, resource endowments, and product yields, resource and factor requirements, and costs for all land management and processing technologies. Data sources involve observations, statistics, calculations, model outputs, values taken from the scientific literature, and personal communications with experts. In the following, we describe the major data sources for resources, land management technologies, and commodity markets.

The bottom-up structure of the model is especially manifest through the comprehensive database on agricultural resources (Skalsky et al., 2008). This database contains harmonized geo-spatial data on soil, climate/weather, topography, land cover/use, and crop management from research institutes such as NASA, the European Joint Research Centre, the Food and Agricultural Organization, the United States Department of Agriculture, and the International Food Policy Research Institute. Common spatial resolution layers include 5 and 30 arcmin but also country layers. The variation in natural conditions is captured by Homogeneous Response Units (HRU) defined on relatively stable landscape parameters which are almost constant over time regardless of climate or land use changes.

Crop production data are taken from FAOSTAT, where national averages over the years 2001-2005 are used to define base levels for yields, harvested areas, prices, production, consumption, trade, and supply utilization. Irrigated crop yields, crop specific irrigation water requirements, and costs for five irrigation systems are derived from a variety of sources as described in Sauer et al. (2008). Irrigation system capacities are computed for each region and depend on soil types and slope (Sauer et al. 2008). Management and land quality specific yield impacts[8] are estimated with the Environmental Policy Integrated Climate model (EPIC, Williams 1995, Izaurralde et al. 2006). The model also provides soil carbon, nutrient loss, and erosion impacts. Biofuel options from crops include first generation technologies for a) ethanol from sugarcane or corn, and b) biodiesel from soya or rapeseed. The processing data are based on Hermann and Patel (2007) for ethanol and Haas et al. (2006) for biodiesel. Market demand for ethanol and biodiesel is represented through vertical demand functions. Regional livestock production activities are derived from FAOSTAT data. Livestock emissions are computed following IPCC data and guidelines as described in de Cara et al. (2005).

The traditional forest sector representation is based on the 4DSM model developed by Rametsteiner *et al*. (2007). Market data for saw timber and pulp are taken from FAOSTAT. Production costs are compiled from an internal database at IIASA's forest program. Data on industrial wood plantations are estimated by Xiaozhen (2007). The biomass of these plantations can be converted into methanol and heat or electricity and heat, where processing costs and conversion coefficients are obtained from Leduc et

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[8] Alternative management regimes are only available for selected crops.

al. (2008), Hamelinck and Faaij (2001), Sørensen (2005), and Biomass Technology Group (2005). Demand for woody bioenergy production is vertical, i.e. implemented through minimum quantity restrictions. Greenhouse gas impacts for forests are based on IPCC estimates (Nabuurs et al. 2007)

Scenarios

Development is a complex process, which involves numerous changes. Through scenarios, we are able to analyze both partial and combined impacts for some of these changes. In this study, we consider six important drivers of development: a) population, b) per capita income, c) land endowments, d) fresh water availability, e) technical progress, and f) environmental policies. These drivers are exogenously determined. Population and income development assumptions are based on SRES scenarios (Nakicenovic and Swart 2000). Particularly, we use the estimates of the A2r path for 2030. In turn, the estimates of population and income growth are used to calculate supply shifts for land and water and demand shifts for agricultural products. Land shifts are computed by multiplying regional specific urban population densities with the incremental increase in population. The product is used to shift the land supply function leftwards from the 2005 equilibrium point. Similarly, water supply is decreased by the product of population increase and water use coefficients. For scenarios, which consider both population and economic development, we also apply a global income elasticity of 0.5 to reflect increased water demand as income grows (Dalhuisen et al. 2003). Commodity demand shifts are computed in 2 stages. First, all demand functions are shifted from the basic equilibrium point proportional to the population increase. Second, for all scenarios which include economic development, we shift the demand curves by applying income and commodity specific income elasticities. Generally, these elasticities are higher at lower income levels and for animal products.

We distinguish three technical progress assumptions. In addition to a zero progress scenario, we assume yield increases for all included crop and livestock products with rates of 20 and 40 percent from 2005 to 2030.These increases correspond to a geometric annual mean increase of 0.73 and 1.35 percent, respectively. Note that all yield increases are assumed to be cost-free. Different rates are used to show the partial impact of technical progress and to portray the uncertainty about future improvements. While some argue that technological breakthroughs will sustain past decades' progress rates, others fear that productivity growth may have reached a plateau (Calderini et al. 1998, Cassman et al. 2003). The 40 percent growth rate is well in line with studies such as Egli (2003), who found soybean yield increase of 30 to 45 percent between 1972 and 2003 for locations in the mid-western USA.

Environmental policy scenarios involve alternative assumptions regarding a) the permission of deforestation, b) the demand for bioenergy, and c) carbon emission markets. Deforestation is either fully permitted or fully prohibited. Bioenergy demand is zero or 5 percent of the total projected energy demand in 2030. Carbon emission markets are either non-existing or implemented at a level of 100 USD per ton of carbon equivalent. Together, these alternatives yield eight environmental policy combinations. In total, we examine 364 scenarios which result from a 2005 base solution and 33 development assumptions over 11 steps. The 11 steps are equally spaced between 0 and 1 and represent different degrees of change with 0 representing the state of population, water, land, and GDP in 2005 and 1 the state in 2030. Intermediate values apply only the corresponding fraction of change from 2005 and 2030. Note that environmental policy and technical progress assumptions are fully implemented across all steps.

To ease the readability of scenario results we use the abbreviations with the following interpretations: Popl. = Scenario includes population growth impact on commodity demand, GDP = Scenario includes income change impact on commodity demand, Land = Scenario includes population growth impact on land scarcity, Water = Scenario includes population growth impact (and income change effect if GDP is also included) on water scarcity, 20% (40%) = Scenario includes technical progress of the specified rate, No deforest. = Scenario does not allow deforestation, CO2-Tax = Scenario applies a 100 USD per metric ton of carbon (mtce) equivalent tax on all greenhouse gas accounts, Bioenergy = Model enforces bioenergy production equaling 5 percent of the 2030 energy demand. If not otherwise specified, the scenarios include technical progress, zero greenhouse gas tax, zero bioenergy demand, and full deforestation permission.

Results

This section shows empirical results from the above described scenario simulations. Thereby, the size of the model forces us to be highly selective. Note that a single solution already contains several millions of endogenous variable and equation values. Accordingly higher is the output from 364 scenarios. To present the simulation results within the scope of a journal article, we focus on aggregate measures. The use of aggregates has three additional advantages beyond brevity. First, as argued in Onal and McCarl (1991), sector models, while using more resolved data, perform better on the aggregated level. This holds in particular for our model which is calibrated over 11 global regions. Second, aggregate measures contain and summarize many individual measures simultaneously. Third, the efficiency of policies – in a potential pareto optimality sense - can only be judged at the aggregated level.

Agricultural Land and Water Intensities

Major market and non-market impacts of agriculture are driven by the total amount of land used for the production of food and by the intensity of land management both with respect to inputs and outputs. Total cultivated land for food and other traditional agricultural products is shown in Figure 1. The left side displays the impact of technological progress and climate policies for population and average income levels of 2005. We find that a greenhouse gas tax of 100 $/mtce decreases agricultural land by more than 10 percent. The impact of technical progress is considerably smaller even for a high progress rate of 40 percent. Note that technical progress and greenhouse gas taxes affect food production in opposite ways. While technical progress decreases the marginal cost of food production, a greenhouse gas tax will increase it. Moving from left to right in Figure 1 shows how population and income development further influence the amount of cultivated land. Interestingly, if population growth occurs without income growth, the amount of land decreases indicating that the scarcity effect exceeds the increased demand effect. However, using the projected income development, global cultivated land use increases. The income based land increase is roughly compensated by a 20 percent rate of technical progress.

Increases in land for food production decreases the total area of native forests. This is displayed in Figure 2. We observed substantial deforestation if development is not coupled with environmental policies. Note that the deforestation estimates do not include the impact of land degradation and therefore should be considered conservative. Technical progress can mitigate the extent of deforestation but even under relatively high progress assumptions of 40 percent, deforestation is still substantial. However, as shown in Figure 2, a global greenhouse gas tax would provide a much higher disincentive for deforestation. In all development scenarios where we apply a 100$/mtce greenhouse gas tax, deforestation is negligible. Internalization of greenhouse gas emissions even at relatively low prices makes deforestation very expensive because of the high greenhouse gas release (Nabuurs et al. 2007). Deforestation is also a coarse indicator for ecological losses. If these losses would be internalized, the greenhouse gas price threshold, which prevents deforestation would be substantially below 100 $/mtce.

Irrigation is an important adaptation option for farmers. According to Rosegrant et al. (2002), average irrigated yields of cereals are almost twice as high as average rainfed yields. Obviously, the more water deficient a region is the higher are yield differences between irrigated and rainfed cropping systems. However, the economic attraction of irrigation is only given, if the increased marginal revenue from higher crop yields outweighs increased costs. Net benefits of irrigation are difficult to quantify because revenues and costs depend both on local characteristics and regional or global feedback mechanisms. Particularly, marginal revenue changes depend on yield differentials and commodity prices. All activities which lead to higher commodity prices increase the economic attractiveness of irrigation. On the cost side, all activities which lead to more water scarcity decrease the economic attractiveness of irrigation.

In showing the complex response of irrigation to development, we focus on three types of information: a) total area under irrigation (Figure 3), b) total water use through irrigation (Figure 4), and c) average water use per irrigated hectare (Figure 5). We find that all scenarios which include population growth based demand shifts increase the area under irrigation. Without environmental policies, increases from 2005 to 2030 range between 45 and 55 percent depending on technical progress. In contrast, land demanding environmental policies, as exemplified by the no deforestation and 5 percent bioenergy policy, increase irrigated land in 2030 by 75 percent relative to 2005. The overall water use does not mirror the change in irrigated area. If only resource scarcity is considered, overall agricultural water use decreases by about 5 percent from 2005 to 2030. However, considering both resource scarcity and population growth, we find a more than 10 percent increase. Income development further raises water use by at least 5 additional percent.

Several non-linear responses can be observed. The basic development scenario (water, land, population, GDP) results in a more than 10 percent total water use increase if population and economic development assume half the change estimated for 2030. Subsequently, water use decreases by 5 percent and shortly before 2030 values are reached, total agricultural water use starts to increase again. Technical progress does not generally decrease agricultural water use.

Food Security

Food security impacts are identified by food consumption levels but are driven by income and prices for food. In our analysis, all agricultural commodity prices are endogenously determined for each development scenario. Figure 6 shows the world market price impacts aggregated over all crops. These price changes represent average long-term differences in real prices. It can be noted that all scenarios fall roughly in one of three bundles: a) almost no price change, b) medium price increases of 30 to 45 percent by 2030, and c) higher price increases between 80 and 135 percent. All development scenarios in the first bundle contain only an increase in land and water scarcity but keep food demand constant. The second bundle contains development scenarios, where food demand is shifted according to population growth. Finally, the third bundle contains scenarios where demand is shifted due to population and income growth. The results displayed in Figure 6 suggest that food prices are more affected by expected changes in food demand than by the rate of technical progress or moderate environmental policies.

The impacts of development scenarios on food consumption are shown in Figure 7-Figure 10. We focus on three aspects: a) per capita consumption of vegetarian food, b) per capita consumption of non-vegetarian food, and c) the relative share of non-vegetarian food. Furthermore, we compare average global impacts (Figure 7) versus regional impacts by comparing Western European countries (Figure 10), centrally planned economies of Asia (Figure 9), and sub-Saharan countries of Africa (Figure 8). On the global level, the following observations can be made. The effect of population growth induced land and water scarcity on average food intake is small. The impact of increased population on per capita intake of both vegetarian and animal based food is more noticeable. If increased population growth and income development are considered simultaneously, we find an increase in non-vegetarian food consumption both in absolute and relative values. Vegetarian food intake is somewhat lower compared to the 2005 baseline but the reduction is much less than without income changes.

The added impact of technical progress and environmental policy shows in bars 5 to 12 of Figure 7-Figure 10. Without technical progress, the 5% bioenergy target and a global deforestation ban decrease global vegetarian food use per capita by about ¼ relative to 2005. However, the average livestock product consumption levels per capita remain similar and thus, the average share of non-vegetarian food increases. Moderate technical progress, as assumed under the 20% yield increase scenario, is sufficient to compensate for increased land and water scarcity and the projected increase in people. However, when development also leads to environmental policies, a much higher progress rate may be required to maintain global average per capita food consumption levels of 2005. For example, 20 percent yield progress over 25 years is not sufficient to overcome the effects of a 5 percent bioenergy target with zero deforestation allowance.

Comparing alternative environmental policies, we find different responses regarding the composition of food. Comprehensive greenhouse gas policies leave the global average ratio of animal food to vegetarian food relatively unaffected regardless whether the technical progress rate is 0, 20, or 40 percent. Thus, increased marginal costs due to livestock emissions and land scarcity roughly cancel the increased marginal revenue due to income based demand shifts. However, climate policies, which focus only on bioenergy offsets and prevention of deforestation, affect food production cost solely through increasing opportunity costs on land. For relatively low bioenergy targets, these marginal cost increases are lower than the increases in marginal revenue due to income based demand shifts. Hence, the share of animal food increases.

Figure 8-Figure 10 show food consumption impacts in different regions. Different income development projections drive regional results apart. While the A2r projection of population and income development decrease the average per capita food consumption in Europe and Sub-Saharan Africa, substantial increases occur in China and other planned economies of Asia with the average consumption of non-vegetarian food more than doubling. The beneficial effects of income growth in planned economies of Asia more than compensates possible costs of environmental policies regardless whether technical progress is at historical pace or below.

Summary and Conclusions

Land use related interdependencies between population, water, food, and environmental policies are important drivers for the welfare of current and future generations. Little doubt exists that political interference is needed to make the best out of these interdependencies. Most of these complex interdependencies are well-known on a qualitative level. However, efficient political interference requires scientific guidance via quantitative assessments to be able to find the best compromise between conflicting objectives. This paper uses a global, bottom-up, partial equilibrium model of land use to assess these interdependencies in the context of different development scenarios. The chosen modeling approach fills a gap between on the one hand coarse, top-down, computable general equilibrium models and on the other hand data rich geographic analyses, which keep land management responses, commodity prices, and international trade exogenous.

From the application of this model to common development scenarios, we gain the following general insights. First, in absence of strong environmental policies, maintenance of agricultural productivity growth as observed in recent decades appears sufficient to counter increased food demand and resource scarcity at the global level in the next two to three decades. Second, income growth impacts generally outweigh the impacts of increased scarcity of land and water. As a result, the average consumption of non-vegetarian food increases. Third, increased consumption of non-vegetarian food increases prices for both vegetarian and non-vegetarian food. Fourth, population and income growth increases potential land expansion into forests. However, deforestation can be mitigated considerably through technical progress or completely avoided through global greenhouse gas taxes. Fifth, a relatively small bioenergy target of 5 percent of total energy supply already causes notable negative impacts on food security. As the target increases, the impact of bioenergy increases more than proportional. Thus, in absence of technological breakthroughs both with respect to food and non-food agriculture, the relative contribution of bioenergy to total energy supply is limited. Sixth, the complex interactions between different drivers of land use can cause highly non-linear impacts. Regional gains and losses do not mimic average global changes. This confirms the necessity to analyze land use in an integrative manner, which accounts both for local variations in natural conditions and technology and global, international market feedback.

Several limitations to this work need to be mentioned. First, the solution values of mathematical programming models are point estimates without confidence interval. Second, the accuracy of model results depends on the quality of the data. Note that the probability that data errors are detected increases as the magnitude of an error increases. Third, for all development scenarios, we have assumed equal rates of technical progress. Different rates could substantially alter regional distributions of impacts. Fourth, our analysis does not account for adjustments in industrial sectors. Fifth, climate change impacts on agriculture are currently neglected.

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References

Biomass Technology Group (2005). Handbook Biomass Gasification. H.A.M. Knoef. ISBN: 90-810068-1-9.

Calderini,D.F. and G.A.Slafer. 1998. "Changes in yield and yield stability in wheat during the 20th century." *Field Crops Research*. 57:335-347.

Cassman,K.G., A.Dobermann, D.T.Walters, and H.Yang. 2003. "Meeting Cereal Demand While Protecting Natural Resources and Improving Environmental Quality." *Annual Review of Environment and Resources*. 28:315-358.

Dalhuisen,J.M., R.J.G.M.Florax, H.L.F.Groot, and P.Nijkamp. 2003. "Price and Income Elasticities of Residential Water Demand: A Meta-Analysis." *Land Economics*. 79:292-308.

De Cara,S., M.Houze, and P.A.Jayet. 2005. "Methane and nitrous oxide emissions from agriculture in the EU: A spatial assessment of sources and abatement costs." *Environmental & Resource Economics*. 32:551-583.

Diamond, Jared (2005). *Collapse: How Societies Choose to Fail or Succeed*. New York: Viking Books. ISBN 1-586-63863-7.

Egli,D.B. 2008. "Soybean yield trends from 1972 to 2003 in mid-western USA." *Field Crops Research*. 106:53-59.

FAOSTAT. 2005. Available online at faostat.fao.org.

Gerbens-Leenes,W. and S.Nonhebel. 2005. "Food and land use. The influence of consumption patterns on the use of agricultural resources." *Appetite*. 45:24-31.

Haas, McAloon, Yee, Foglia, 2006, ‘A process model to estimate biodiesel production costs’, Bioresource Technology, Vol. 97, Issue 4, Page 671-678.

Hamelinck, C.N. and A.P.C. Faaij (2001). “Future Prospects for Production of Methanol and Hydrogen from Biomass.” Utrecht University, Copernicus Institute, Science Technology and Society, Utrecht, Netherlands 2001.

Heistermann,M., C.Muller, and K.Ronneberger. 2006. "Land insight? Achievements, deficits and potentials of continental to global scale land-use modeling." *Agriculture Ecosystems & Environment*. 114:141-158.

Hermann, Patel, 2007, ‘Today's and tomorrow's bio-based bulk chemicals from white biotechnology - A techno-economic analysis’, Applied Biochemistry and Biotechnology, Vol. 136, Issue 3, Pages 361-388.

Izaurralde, R.C., J.R. Williams, W.B. McGill, N.J. Rosenberg, and M.C. Quiroga Jakas. 2006. Simulating soil C dynamics with EPIC: model description and testing against long-term data. *Ecological Modelling*, 192:362-384.

Lambin,E.F., M.D.A.Rounsevell, and H.J.Geist. 2000. "Are agricultural land-use models able to predict changes in land-use intensity?" *Agriculture, Ecosystems & Environment*. 82:321-331.

Leduc, S., D. Schwab, E. Dotzauer, E. Schmid, M. Obersteiner (2008). "Optimal Location of Wood Gasification Plants for Methanol Production with Heat Recovery." *International Journal of Energy Research*, IGEC-III special issue.

Nabuurs, G.J., O. Masera, K. Andrasko, P. Benitez-Ponce, R. Boer, M. Dutschke, E. Elsiddig, J. Ford-Robertson, P. Frumhoff, T.Karjalainen, O. Krankina, W.A. Kurz, M. Matsumoto, W. Oyhantcabal, N.H. Ravindranath, M.J. Sanz Sanchez, X. Zhang, 2007: Forestry. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nakicenovic N. and Swart, R.J. (2000) Emissions Scenarios 2000 – Special Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

Onal,H. and B.A.Mccarl. 1991. "Exact Aggregation in Mathematical-Programming Sector Models." *Canadian Journal of Agricultural Economics-Revue Canadienne D Economie Rurale*. 39:319-334.

Rametsteiner E, Nilsson S, Boettcher H, Havlik P, Kraxner F, Leduc S, Obersteiner M, Rydzak F, Schneider U, Schwab D, Willmore L (2007). Study of the Effects of Globalization on the Economic Viability of EU Forestry. Final Report of the AGRI Tender Project: AGRI-G4-2006-06 [2007]. http://ec.europa.eu/agriculture/analysis/external/viability_forestry/index_en.htm

Rosegrant M.W., X. Cai and S.A. Cline, *Global Water Outlook to 2025: Averting an Impending Crisis*, A Report Summary of the 2020 Vision for Food, Agriculture and the Environment Initiative, International Food Policy Research Institute, Washington DC and International Water Management Institute, Colombo, 2002

Sauer, T., Havlik, P., Kindermann, G., and Schneider, U.A. 2008. Agriculture, Population, Land and Water Scarcity in a changing World - the Role of Irrigation. Paper prepared for the 2008 Congress of the European Association of Agricultural Economists in Gent, Belgium.

Schneider,U.A., B.A.McCarl, and E.Schmid. 2007. "Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry." *Agricultural Systems*. 94:128-140.

Skalsky, R., Z. Tarasovičová, J. Balkovič, E. Schmid, M. Fuchs, E. Moltchanova, G. Kindermann, and P. Scholtz. 2008. GEO-BENE global database for bio-physical modeling v. 1.0 – concepts, methodologies and data. The GEO-BENE database report. International Institute for Applied Systems Analysis (IIASA), Austria, pp. 58.

Skalsky, R., Z. Tarasovičová, J. Balkovič, E. Schmid, M. Fuchs, E. Moltchanova, G. Kindermann, and P. Scholtz. 2008. GEO-BENE global database for bio-physical modeling v. 1.0 – concepts, methodologies and data. The GEO-BENE database report. International Institute for Applied Systems Analysis (IIASA), Austria, pp. 58.

Sørensen, Å.L (2005) "Economies of Scale in Biomass Gasification Systems." IIASA, Interim Report 2005, IR-05-030.

United Nations. 2004. World urbanization prospects: The 2003 revision. Department of Economic and Social Affairs, Population Division, New York

Van der Werf, E. & Peterson, S. (2007), "Modeling linkages between climate policy and land use: An overview". FEEM Working Papers 56.2007, Fondazione Eni Enrico Mattei, Milano, Italy.

Wiborg, T., B.A. McCarl, S. Rasmussen, and U.A. Schneider (2005), "Aggregation and Calibration of Agricultural Sector Models Through Crop Mix Restrictions and Marginal Profit Adjustments."

Williams, J.R. 1995. *The EPIC Model.* In *Computer Models of Watershed Hydrology* (Ed.: V.P. Singh). Water Resources Publications, Highlands Ranch, Colorado, 1995, pp 909-1000.

Xiaozhen, L. (2007). Personal communication. IIASA

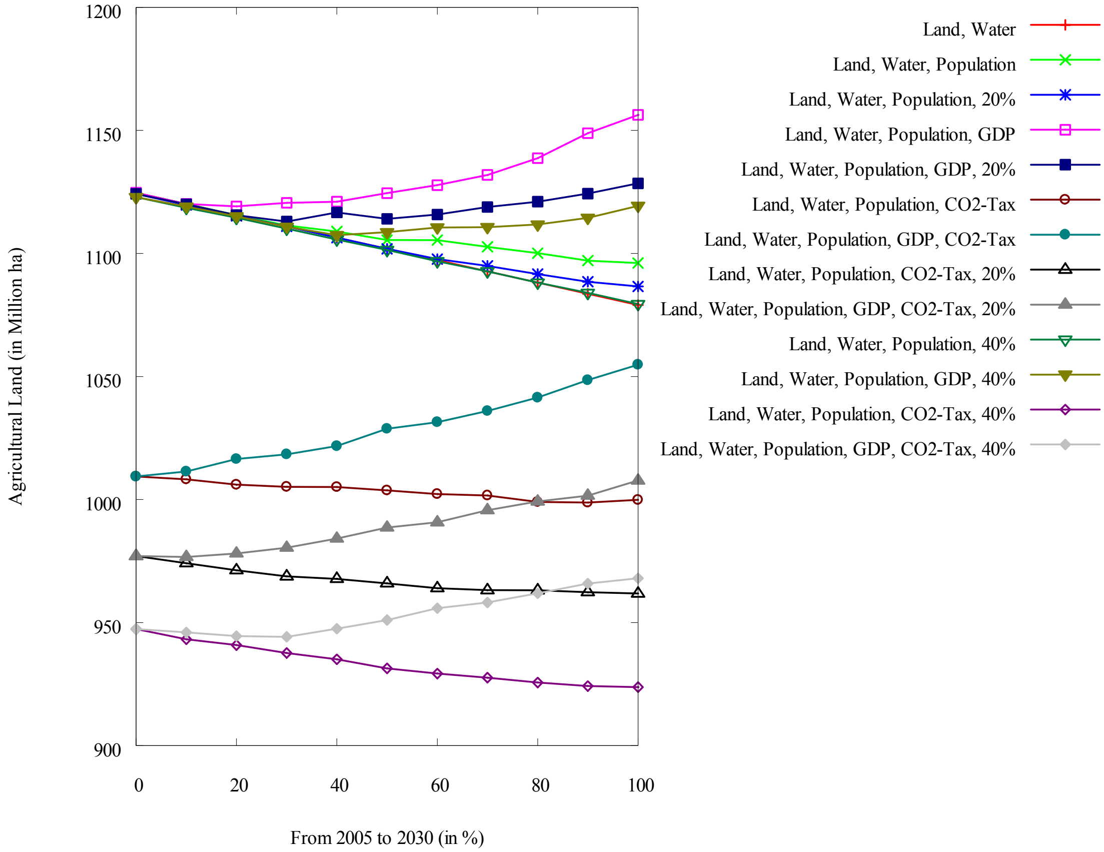

Figure 1 Global land area used for cultivated crops

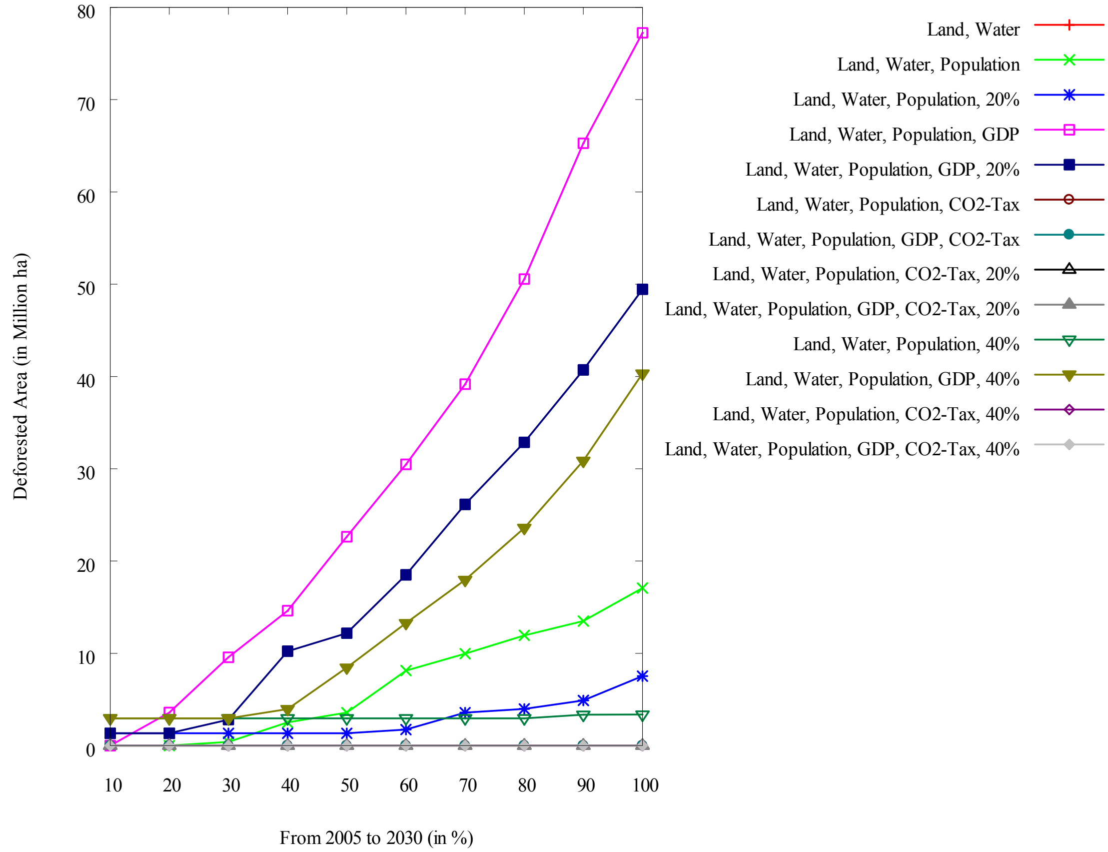

Figure 2 Global deforested area

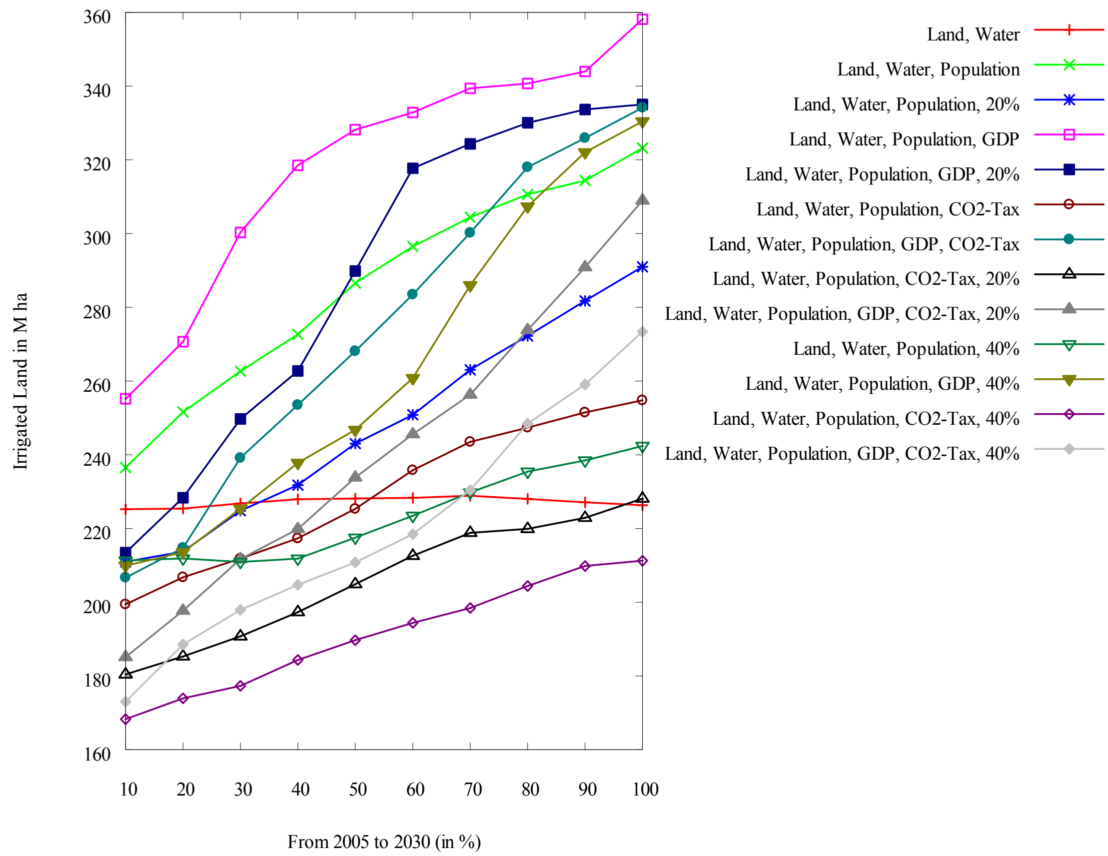

Figure 3 Global irrigated land

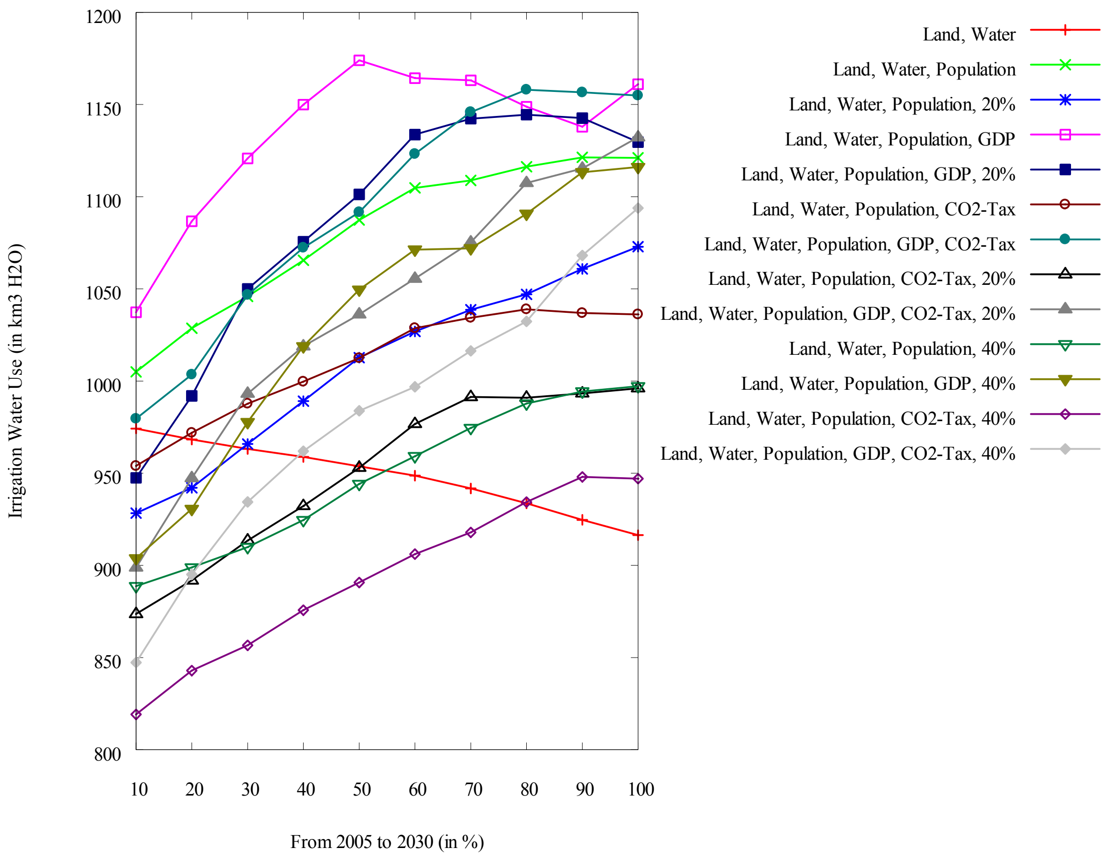

Figure 4 Global water use for irrigation

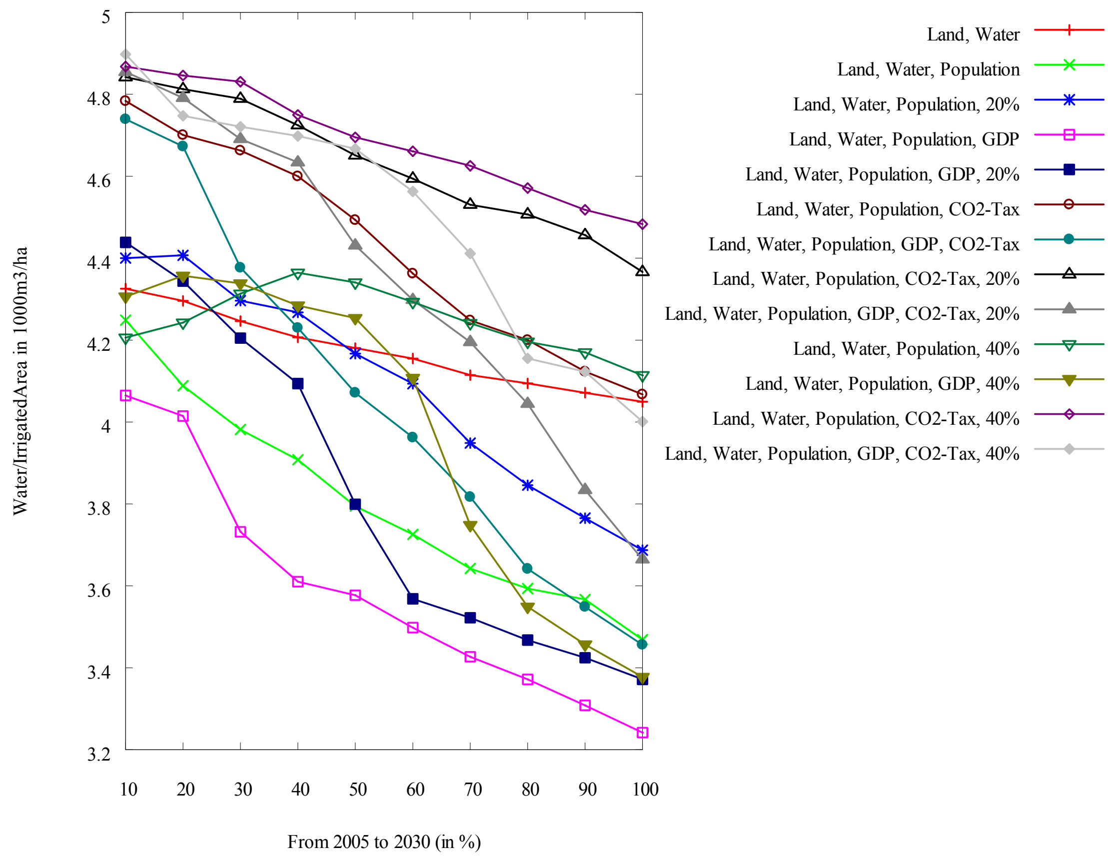

Figure 5 Irrigation intensity

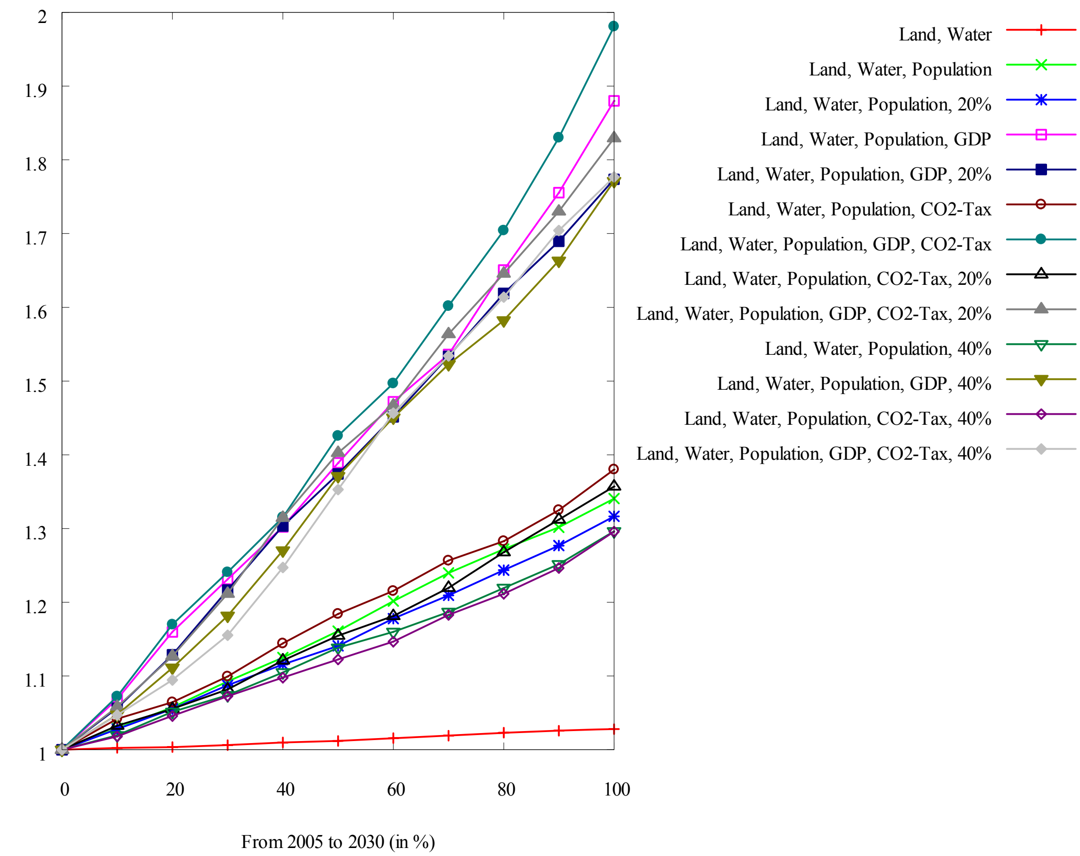

Figure 6 World market price index for crops

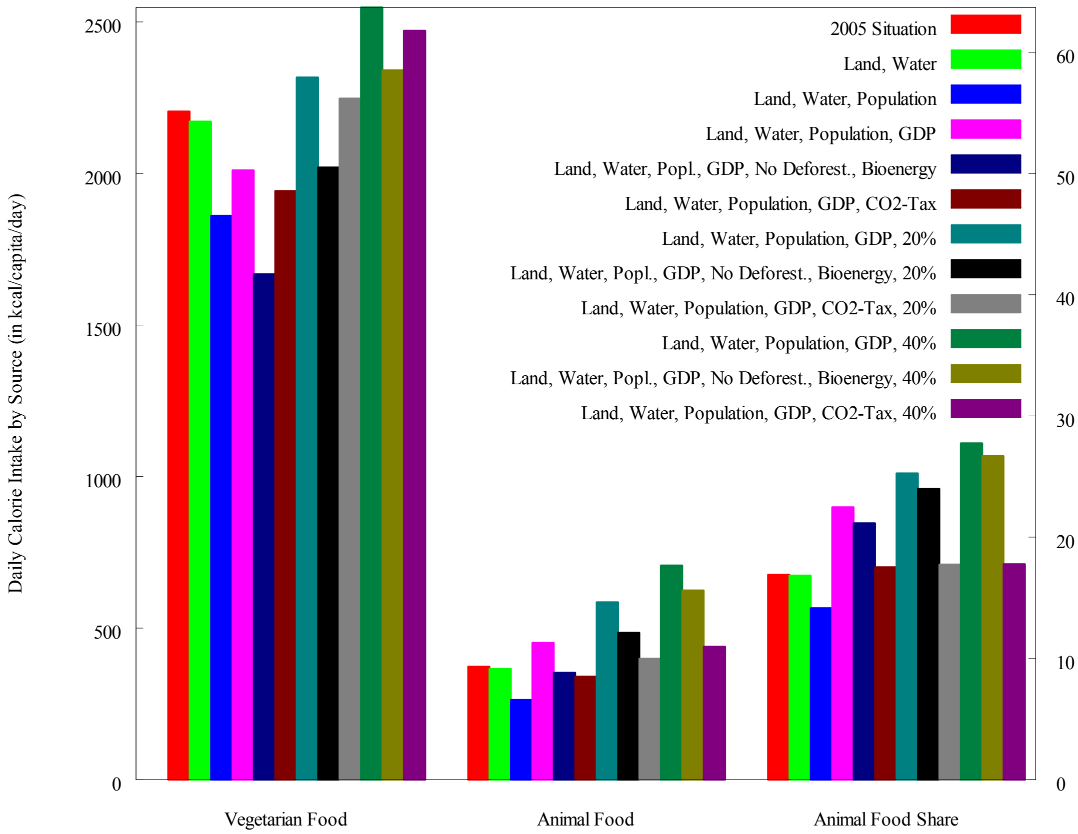

Figure 7 Global food consumption and composition[9]

[9] Animal food shares correspond to the right vertical scale.

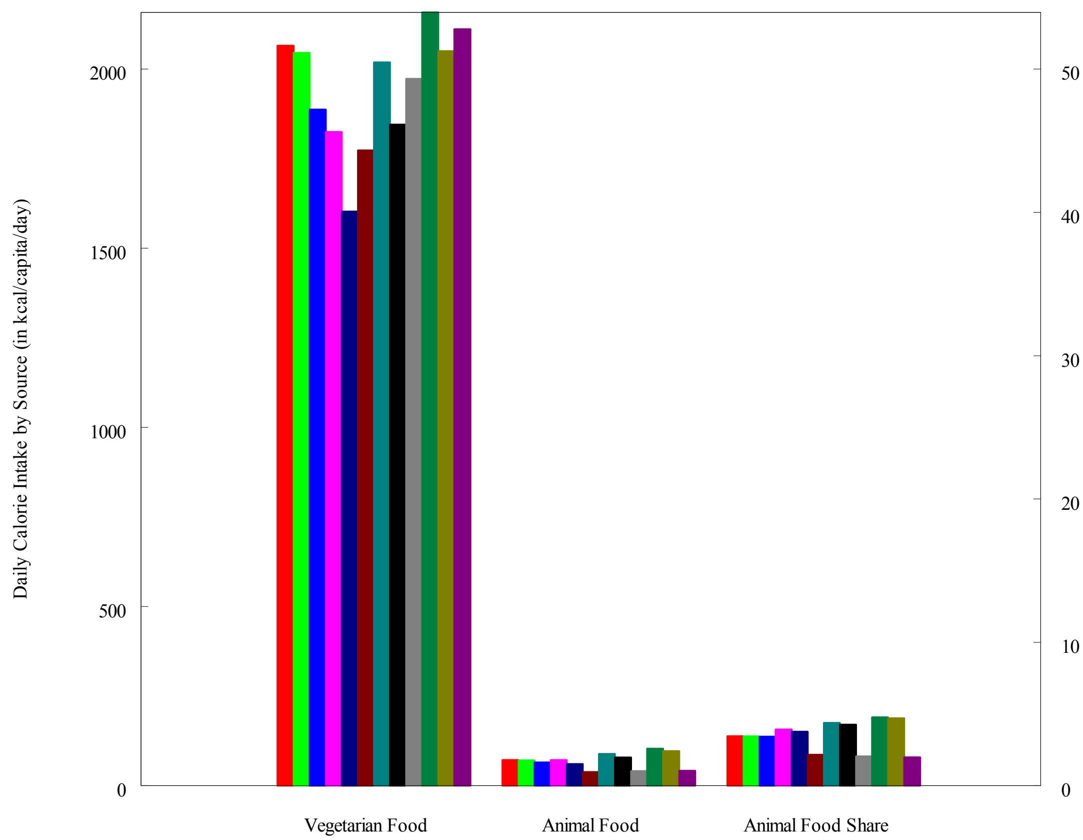

Figure 8 Food consumption and composition in Sub-Saharan Africa[10]

[10] The legend of Figure 7 applies.

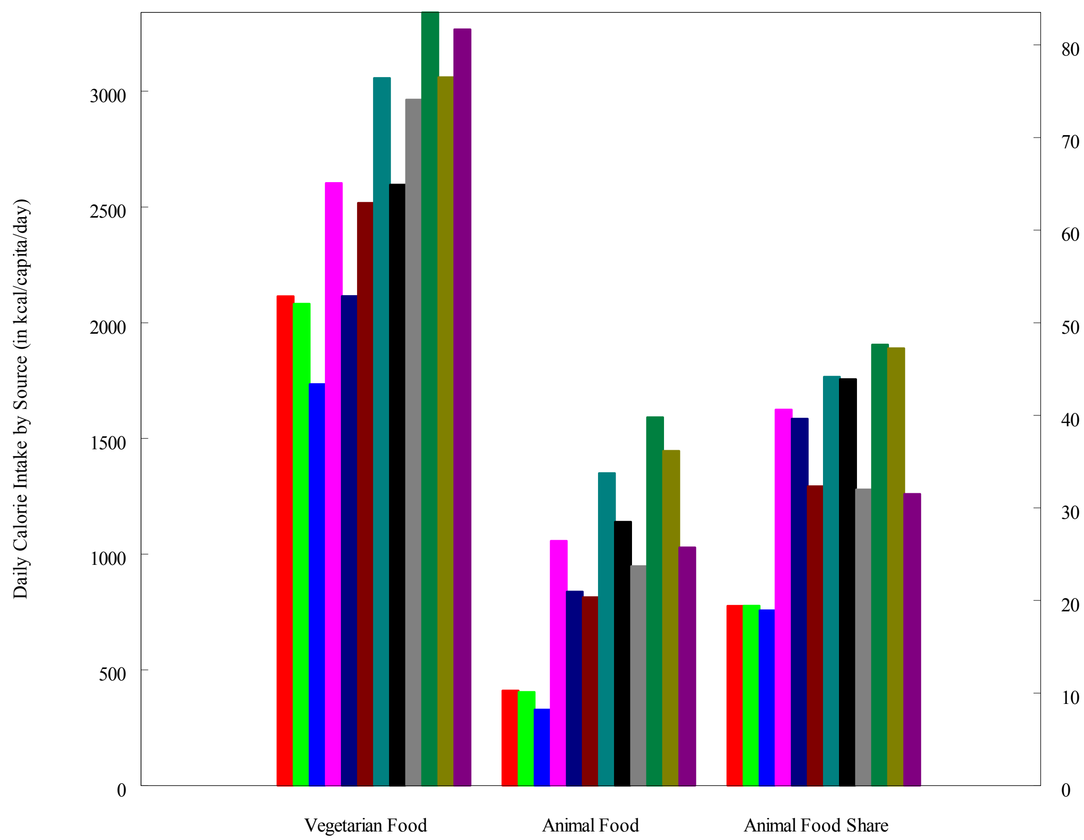

Figure 9 Food consumption and composition in planned economies of Asia[10]

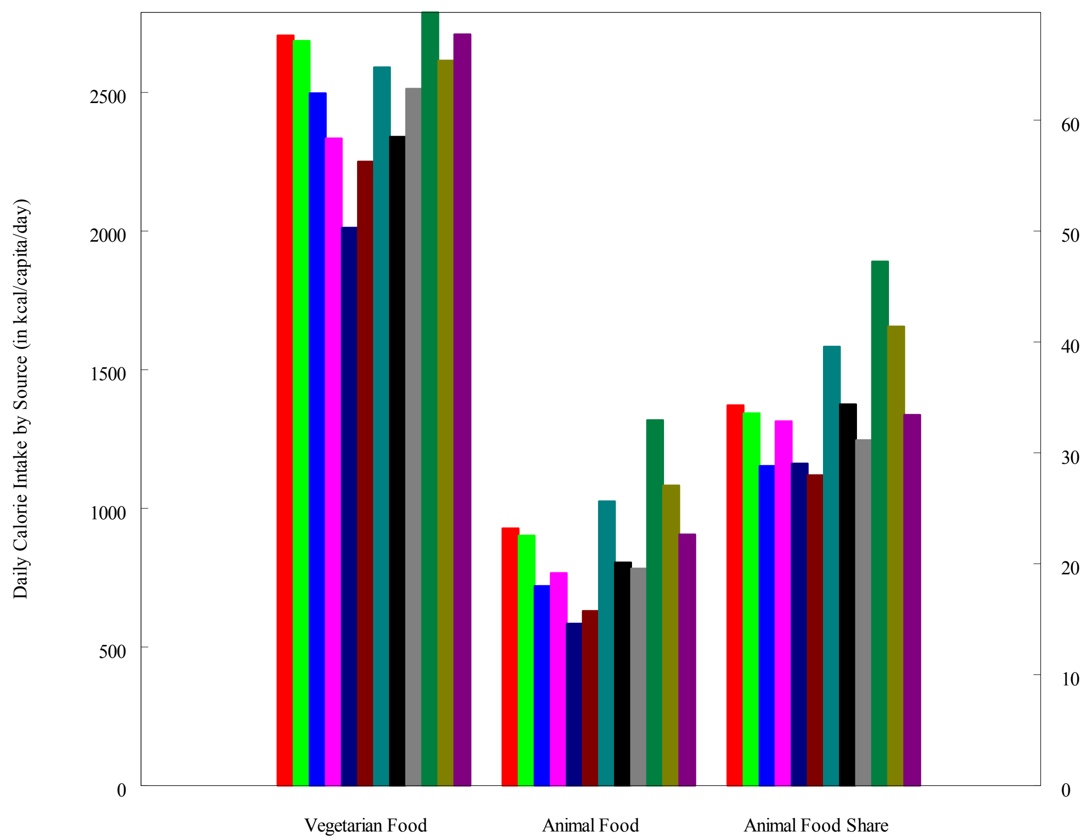

Figure 10 Food consumption and composition in Western Europe[10]

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Evaluating the efficiencies of crop production systems within an Integrated Data Envelope Framework

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Evaluating the efficiencies of crop production systems within an Integrated Data Envelope Framework[1]

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Abstract – Analyzing the potential of crop yields and the effects of crop management is essential to support policy decisions that foster sustainable agricultural systems. We apply a non-parametric Integrated Data Envelopment Analysis (IDEA) to evaluate technically efficient crop management systems by considering positive and negative externalities like soil organic carbon sequestration, nitrogen emissions and soil sediment losses. Providing relative efficiency measures, IDEA is based on simulation outputs from the biophysical process model EPIC (Environmental Policy Integrated Climate), which simulations comprise five thematic datasets: (i) land cover/land use data, (ii) topographical data, (iii) soil data, (iv) crop management data, and (v) climate data for 25 European member states (EU25). It can be expected that IDEA yields improved efficiency measures by considering positive and negative effects of alternative crop production systems which are simulated with EPIC in context of spatially explicit site and land use characteristics of EU25. The integrated analysis reveals that crop management systems with straw removal yield more and higher efficiency results than without straw removal, and conventional tillage has more technically efficient ratings than other tillage systems, and spring barley, winter wheat and oats are more often found in technically efficient crop rotation systems than other crops.

Keywords: Agricultural production systems; EPIC; Integrated Data Envelopment Analysis; Externalities

1. Introduction

The recent food crisis has motivated discussions on how to satisfy the global demands for cereals. Questions on how crop yields can be increased to satisfying the needs of an increasing world population have dominated agendas of international organizations and associations. These concerns have been fueled by trends of urbanization, income increases in low income countries which usually translate into a higher consumption of food and changing consumption patterns, and assimilations to food preferences of OECD countries with a shift to high processed products (Regmi et al., 2008; Trostle, 2008). In addition, the expansion and growth of the energy markets and their supporting policies are changing the role of agriculture, which is becoming a major provider of feedstock for the production of biofuels such as ethanol and biodiesel. Moreover, sudden impacts, like adverse weather events, speculation or sharp

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increases in global food prices put additional pressure on global crop production in the next decades (Bruinsma, 2003).

Even though technical progress and agricultural intensification over the last decades have ensured a large increase in global food supply (Bruinsma, 2003), these trends seem to flatten out or even turn downwards. An increased crop production has been mainly achieved through the use of high yielding crop varieties, commercial fertilizers and other agro-chemicals, irrigation water, and fossil energy (Foley et al., 2007; Fox et al., 2007; Khan and Hanjira, 2008). Many of these inputs put also pressure on environmental qualities and natural resource utilizations. Hussein and Hanjira (2003, 2004) reported that in recent decades, productivity of irrigated land has been declining. Moreover, soil salinization is spreading further and will reduce soil fertility and agricultural productivity. Effects like climate change can affect food production adversely and, even though it is difficult to make predictions, there is a higher risk for droughts and floods such that crop yield losses are more likely. Another limiting factor to arable land utilization is the degree of land degradation, which is increasing by higher production intensities, shorter fallow periods, intensive tillage, excessive use of agro-chemicals, and monocultural cropping (Bruinsma, 2003). These considerations raise questions such as: Which crop management systems are technically efficient considering positive and negative outputs (agricultural externalities)?

The aim of this analysis is to show which crop production systems are rated as technically efficient in EU25 and which site determining factors (e.g. soils, weather) are influencing the efficiency ranking most. To provide a ranking of technically efficient crop production systems on a regional scale we take following factors into account: (i) site specific differences, like soils, climates, geography and topography, as well as (ii) differences in crop management practices such as fertilizer inputs and irrigation. We apply a non-parametric Data Envelopment Analysis (DEA) using simulation outputs from the bio-physical process model EPIC (Environmental Policy Integrated Climate) to provide a single efficiency measure for each crop production system. EPIC simulates important biophysical processes in agricultural land use management and thereby provides model outputs on e.g. crop yields, nitrogen emissions, and soil organic carbon contents.

The analysis focuses mainly on following research questions: What soil texture classes are favorable for particular crop production choices? Which NUTS2 regions have most technically efficient and environmentally friendly production systems? Which crops are most often found in technically efficient rated crop rotations?

In the course of this analysis we expand the traditional DEA model by integrating undesirable environmental outputs, like nitrogen emissions and soil sediment losses, into an environmentally integrated DEA (IDEA). Efficiency results have proven to be rather sensitive to whether undesirable outputs are included or not. Models including undesirable outputs are expected to yield improved efficiency measures, whereas traditional models without undesirable outputs might give biased indications (Yang and Pollitt, 2009).

By providing insights about technically efficient cultivation and crop management choices in the EU25, we provide a valuable tool to support policy decisions that foster sustainable agricultural systems.

The article is structured such that we describe the analysis method DEA in section 2. In subsection 2.1 we introduce the standard DEA model, which is extended by the integration of undesirable outputs in subsection 2.2, and by the performance of a two-stage approach to account for external factors influencing production efficiency in subsection 2.3. In section 3, we briefly describe the bio-physical process model EPIC, which is followed by the introduction of our model specifications in section 4. Section 5 provides results of the efficiency analysis, whereby we focus on technically efficient crop management systems in 5.1, the geographic distribution of technically efficient production units in 5.2, the distribution of crops in technically efficient production units in 5.3, and the distribution of soil texture classes of technically efficient production units in 5.4. In 5.5, we introduce external factors influencing the production efficiency. In section 6 we discuss our results and conclude on our findings.

2. Method

2.1. The standard DEA Model

Data Envelopment Analysis (DEA) is a data driven frontier analysis technique to model operational processes for performance evaluation (Cooper, Seiford and Zhu, 2004). It is used to estimate efficiencies of comparable entities, which are called decision making units (DMUs), relative to the other DMUs in the group. A DMU can be any entity with the ability to convert inputs into outputs. Therefore, DEA does not require specific functional assumptions on the production function like Stochastic Production Frontier approach (SPF), which is often restrictive in agricultural production analysis. Instead DEA is a non-parametric method which uses linear programming models to construct a piece-wise surface frontier over the observations. The DMUs which exhibit best practice performance constitute the efficiency frontier of the group, against which the relative efficiencies of the remaining DMUs are measured to. The level of efficiency is identified by benchmarking them with DMUs lying on this frontier (cp. Figure 1) (Coelli, Rao and Battsee, 1998).

In these regards, DEA estimates relative efficiencies: A DMU is rated fully efficient on the basis of available evidence if and only if the performances of other DMUs does not show that some of its inputs or outputs can be improved without worsening some of its other inputs or outputs (Cooper, Seiford and Zhu, 2004).

Basically, three efficiency concepts can be distinguished in a DEA:

(i) technical efficiency, which focuses on the performance and possibility of a DMU to yield maximal output from a given bundle of inputs and technology. According to Farrell (1957) technical efficiency is always estimated relative to the best observed performance in the group. The evaluation of technical efficiency is central to our analysis,

(ii) allocative efficiency, which denotes the ability of a unit to use the inputs in optimal proportions given their respective prices and production technologies. Technical efficiency and allocative efficiency sum up to economic efficiency, and

(iii) scale efficiency, which determines whether the size of the DMU is optimal with respect to its production factors (Coelli, Rao and Battsee, 1998).

Apart from technical efficiency, the concept of scale efficiency plays also a role in our analysis as well. The size of a DMU is measured in production units and the optimal size is where the factor productivity is highest. The assumption of constant returns to scale (CRS) suggests that all DMUs are operating at an optimal scale and therefore have the optimal size (Coelli, Rao and

Battsee, 1998). The use of constant returns to scale, when not all units are operating at the optimal scale, results in measurements of technical efficiency which are confounded by scale inefficiencies. In this case, the application of the variable returns to scale (VRS) constraint is appropriate, which forms a convex hull over the data points (cp. Figure 2). A convexity constraint ensures that inefficient DMUs are only benchmarked against DMUs of the same size. VRS provides technical efficiency scores which are greater or equal than those obtained using a CRS model. In the CRS case, a DMU might be benchmarked against a DMU which is substantially larger or smaller (Coelli, Rao and Battsee, 1998).

Furthermore, there is a distinction between input and output orientated models. Input oriented models estimate how the inputs of a technically inefficient DMU can be reduced to reach the efficiency frontier keeping outputs constant. An output oriented model requires a proportional augmentation of outputs in order to reach the efficiency frontier without altering the input quantities. For CRS, input and output oriented models yield the same efficiency measure.

The DEA model with CRS and input orientation was proposed by Charnes, Cooper and Rhodes (1978) and is usually referred to as CCR model in the literature. The VRS approach has been proposed by Banker, Charnes and Cooper (1984) and is referred to as BCC model.

Figure 1. Input oriented CCR model with constant returns to scale, where DMU P2 lies on the efficiency frontier and other DMU are projected to this frontier in order to determine the degree of inefficiency (cp. Cooper, Seiford and Zhu, 2004)

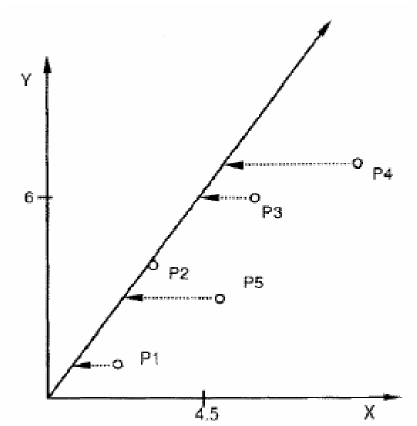
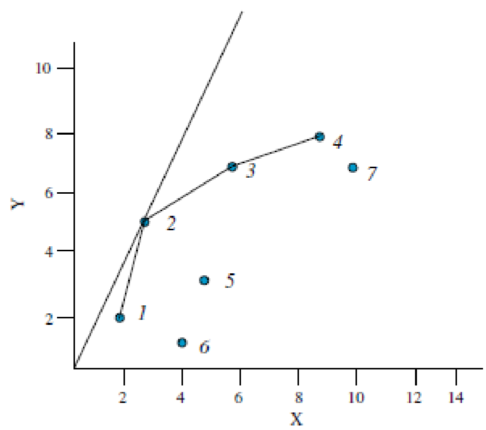


Figure 2. Efficiency frontier for constant returns to scale (linear frontier from the origin) and variable returns to scale (convex hull) for a one input (X) and one output (Y) model. (cp. Cook and Seiford, 2008)



The following formal model representation (1) describes an input oriented BCC model with DMU k = 1,…,K, inputs (x) ranging from n = 1,…,N, and outputs (y) ranging from m=1,…,M. The variable λ is a Kx1 vector giving the distance to the closest efficient DMU for each DMU, and θ^*, a constant, which is the efficiency score for each DMU and indicates the possible proportion of input reduction without reducing outputs in order to reach efficiency.

$$
\begin{aligned}
&\theta^* = \min \theta \\
&\text{s.t.} \\
&\textstyle\sum_{k=1}^{K} x_{kn} \lambda_k \leq \theta x_{k'n} && n = 1, \dots, N \\
&\textstyle\sum_{k=1}^{K} y_{km} \lambda_k \geq y_{k'm} && m = 1, \dots, M \\
&\lambda_k \geq 0 && k = 1, \dots, K \\
&\textstyle\sum_{k=1}^{K} \lambda_k = 1 && \text{(VRS constraint)}
\end{aligned}
\tag{1}
$$

In case of an output oriented model, θ^* indicates the proportion of possible output augmentation for each DMU without increasing inputs in order to reach the efficiency frontier. However, the standard model does not account for situations where positive outputs should not only be increased, but negative outputs (e.g. emissions) should also be reduced. This model will be introduced in the following subsection. Since, we consider negative, environmental outputs like soil sediment losses and nitrogen emissions in a standard DEA we refer it as environmentally integrated DEA, or IDEA. Possibilities to consider categorical inputs in DEA are presented in subsection 2.3.

2.2. Integration of undesirable outputs in DEA

We extend the efficiency estimation by integration of undesirable outputs. There are several ways in which undesirable outputs can be included in a DEA model; we apply an approach presented by Chung, Färe and Grosskopf (1997) and Färe and Grosskopf (2004).

In the model there are $k = 1, \dots, K$ DMUs. The set $P(x)$ denotes the set of desirable outputs $y \in \mathfrak{R}_+^M$ and undesirable outputs $u \in \mathfrak{R}_+^K$ which are producible from the input vector $x \in \mathfrak{R}_+^N$.

The integration of undesirable outputs into this model is based on the assumption that they are:

1. weakly disposable, which is given if $(\mathrm{y}, \mathrm{u}) \in P(x)$ and $\leq \theta \leq 1$ then $(\theta\mathrm{y}, \theta\mathrm{u}) \in P(x)$, implying that e.g. when the negative output is reduced by 10% then the positive output is also reduced by 10%, and
2. null-joint with positive outputs, which is given if $(\mathrm{y}, \mathrm{u}) \in P(x)$, such that $\mathrm{u} = 0$ then $\mathrm{y} = 0$, implying that when good outputs are produced then bad outputs are produced as byproduct.

The integration of undesirable outputs demands the adoption of a directional output distance function instead of the radial distance function which is usually applied. This allows expanding desirable outputs and decreasing undesirable outputs simultaneously. We include a direction vector $g = (g_y, -g_u)$, with $g_y = y_k$ and $-g_u = u_{kj}$, and estimate the efficiency score for DMU k' as the solution to this linear programming problem (Färe and Grosskopf, 2004); λ is a Kx1 vector of constants:

$$
\begin{aligned}
&\max \beta \\
&\text{s.t.} \\
&\sum_{k=1}^{K} x_{kn}\lambda_k \leq x_{k'n} && n = 1,\dots,N \\
&\sum_{k=1}^{K} y_{km}\lambda_k \geq y_{k'm} + \beta g_{y_m} && m = 1,\dots,M \\
&\sum_{k=1}^{K} u_{kj}\lambda_k = u_{k'j} - \beta g_{u_j} && j = 1,\dots,J \\
&\lambda_k \geq 0,\ \sum_{k=1}^{K}\lambda_k = 1 && k = 1,\dots,K
\end{aligned}
\tag{2}
$$

Efficiency is indicated when $\beta = 0$; and inefficiency by positive values of β. Since the direction vector is set in the direction of the observed data, we have the traditional problem subject to the environmental constraint. If the direction vector takes the form $g_y = 1$ and $-g_u = -1$, the solution gives the net improvement of performance in terms of feasible increase in good outputs and feasible decrease in bad outputs (Färe and Grosskopf, 2004).

2.3. Two-stage DEA

The production process is often influenced by external or environmental variables, which are not under the control of the DMU. These could include location characteristics or environmental regulations. If the effect of the environmental variable upon efficiency can be ordered from the least to the most detrimental, then the approach of Banker and Morey (1986) can be used. In this case, each DMU is compared to DMUs with a lower or equal environmental variable (Coelli, Rao and Battese, 2000).

Another method is to stratify the sample according to the environmental variable and perform a DEA for each sub-sample. A problem arising here could be that if the subsample is too small, the degree of discrimination between the DMUs in the data set could suffer. As it will be introduced in section 4, this method has been applied in our analysis.

A third possibility to account for external factors is a two-stage approach, which involves solving a DEA problem using the traditional inputs and outputs in a first stage. In a second stage, the efficiency scores of the first stage are regressed upon the environmental variables with the sign of the coefficients indicating the direction of the influence (u.o. Coelli, Rao, Battese, 2000). For choosing variables for the first and second stage of the analysis it is often assumed that variables in the second stage should affect the efficiency with which the outputs are produced from the inputs. In the one stage-method, the input variables should affect the process of production (Lovell, 1993 in Bradley et al., 2006). When applying the two stage method, the correlation between the variables in the first and second stage needs to be managed, because a high correlation can lead to biased results (Coelli, Rao, Battese, 2000).

The regression can be conducted for instance by ordinary least squares (OLS) regression or by a Tobit regression. Since many of the efficiency scores can take boundary values of 0 or 1, a Tobit regression, which can account for truncated data, is often suggested (Coelli, Rao and Battese, 2000). However, there has been discussion whether the Tobit regression is really appropriate for this kind of data. McDonald (2009) points out that the efficiency frontier can be seen as estimates of true scores relative to a true frontier, and therefore efficiency scores are neither censored nor truncated, or a corner solution of an optimization model, as it has been proposed by Hoff (2007). In cases where Tobit regression is performed on the efficiency scores, Hoff (2007) points out two frequent problems. Firstly, it is often neglected that, contrarily to OLS regression, Tobit regression parameters do not give the effect of the explanatory variable on the DEA scores. Secondly, misspecifications of the regression model should be avoided by choosing carefully between a two-limited or one-limited Tobit regression. Two-limited Tobit regression should only be applied when there is a positive probability of DEA scores on both limiting values and when a significant amount of DEA scores is found on these limits. If the DEA scores have only one limiting value with a positive probability, a one-limited Tobit regression could be performed. But one-limited Tobit regressions assume that the dependent variable is continuous on]-Inf,1] or [0, Inf [, which is also not the case. To avoid these problems Hoff (2007) suggests of the articles from Kieschnick and McCullough (2003) or Papke and Wooldridge (1996) who offer other methods to overcome this problem. Comparing various approaches, Hoff (2007) concludes that OLS performs equally well as other estimators. But OLS will clearly predict scores outside the interval]0; 1], which is often perceived as problematic. Hoff (2007) argues that if the regression coefficients predicted by linear OLS do not differ significantly from the effects predicted from non-linear models, OLS is adequate for modeling these effects. Keeping this argumentation in mind, the two stage regression in the following analysis will be performed using the OLS estimator.

3. Data for an empirical analysis at EU25 scale

The efficiency evaluation is based on simulation outputs from the bio-phyiscal process model EPIC (Environmental Policy Integrated Climate). EPIC simulates major biophysical processes in agricultural land use management. It provides model outputs on e.g. crop yields, nutrient emissions and soil organic carbon stocks and is often used to assess alternative land use and management strategies. The major components in EPIC are weather simulation, hydrology, erosion-sedimentation, nutrient and carbon cycling, pesticide fate, plant growth and competition, soil temperature and moisture, tillage, cost accounting, and plant environment control. EPIC can be used to compare management systems and their effects on crop yields, nutrient emissions, water quality, sediment losses, soil organic carbon sequestration, and greenhouse gas emissions.

The simulation outputs are based on delineated Homogenous Response Units (HRU), (cp. Table 1), which are defined with respect to major landscape characteristics (slope, soil texture, elevation, stoniness, depth to rocks). The integration of the HRU layer with other relevant data (weather, land use, crop management, political boundary layers, etc.) leads to Individual Simulation Units (SimU) (Skalský et al., 2008). These define the spatial interface between EPIC and the DEA model, and serve as DMU. The global digital database (Skalský et al., 2008) is compiled and classified into four groups (global observation data, digital maps, statistical and census data, and results of complex modeling) and comprises five thematic datasets addressing global biophysical modeling aspects:

(i) land cover/land use data,
(ii) topographical data,
(iii) soil data,

(iv) cropland management data, and
(v) climate data

More details on the datasets which are used in the analysis at EU25 scale can be found in the Appendix (cp. Table 7).

Table 1. HRU delineation with respect to elevation, slope, soil texture, depth to rocks, stoniness classes.

Elevation	Slope	Soil texture	Depth to Rocks (DTR)	Stoniness
< 300 m	0-3 %	Coarse	shallow (<40 cm)	< 5%
300-600 m	>3-6 %	Medium	moderate (40-80 cm)	5-25%
600-1100 m	>6-10 %	Medium Fine	deep (80-120 cm)	> 25 %
> 1100 m	>10-15 %	Fine	very deep (> 120 cm)	
	>15-30 %	Very Fine		
	>30-50 %			
	>50 %			

NUTS2 are the political/regional boundaries within SimU are assigned to and resulting in 9555 DMU. For each DMU, a crop rotation system is simulated over 10 years, which usually includes 3-4 different crops. The fertilization rates for each crop are calculated according to nutrient contents in crop yields. The average crop yields for each NUTS2 region are calculated from 10 years of EUROSTAT New Cronos data. Some DMUs are irrigated which are identified by combining CORINE/PELCOM data and LUCAS data. The efficiency analysis is based on average EPIC input and output data from 10 years of simulations. The IDEA inputs include nitrogen fertilizer (FTN) in kg/ha, and irrigation water amounts (IRGA) in mm, desirable outputs include dry matter crop yields (YLDD) in t/ha, dry matter straw yields (YLDS) in t/ha, and topsoil organic carbon stocks (OCPD) in t/ha, and undesirable outputs are total nitrogen emissions in kg/ha and soil sediment losses (MUST) in t/ha (cp. Table 2 for descriptive statistics of these variables)

Each crop rotation system is simulated for six alternative tillage and straw management systems, which will be referred to as crop management systems, such as:

- minimum tillage (~40% of crop residues after crop planting) without and with straw removal,
- reduced tillage (~15% of crop residues after crop planting) without and with straw removal, and
- conventional tillage (~5% of crop residues after crop planting) without and with straw removal.

Table 2. Descriptive statistics of inputs and outputs for the IDEA

	YLDD in nt/ha	YLDS in t/ha	FTN in kg/ha	MUST in t/ha	OCPD in t/ha	N emissions in kg/ha	Irrigation in mm
Conventional tillage without straw removal							
mean	2.653	1.385	110.756	7.334	55.954	160.007	15.307
stand. dev.	1.152	1.761	41.361	10.987	42.981	116.632	39.602
Conventional tillage with straw removal							
mean	2.652	2.900	110.756	7.453	55.236	161.675	15.307
stand. dev.	1.156	1.775	41.361	11.097	42.889	116.989	39.602
Minimum tillage without straw removal							
mean	2.468	1.316	110.756	5.712	57.571	146.988	15.307

stand. dev.	1.038	1.634	41.361	9.608	43.482	106.209	39.602
Minimum tillage with straw removal							
mean	2.527	2.810	110.756	6.461	56.711	147.365	15.307
stand. dev.	1.079	1.730	41.361	10.231	43.340	108.754	39.602
Reduced tillage without straw removal							
mean	2.576	1.360	110.756	6.421	56.916	151.472	15.307
stand. dev.	1.112	1.712	41.361	10.203	43.388	108.680	39.602
Reduced tillage with straw removal							
mean	2.608	2.870	110.752	6.875	56.192	151.110	15.307
stand. dev.	1.135	1.765	41.361	10.560	43.287	109.871	39.602

4. Model specification

In our study we apply an output oriented IDEA with undesirable outputs and VRS to ensure that a DMU is only compared to DMUs of comparable size, ($\sum_{k=1}^{K} \lambda_k = 1$). Furthermore, we take into account external factors such that we (i) stratify the sample by soil texture classes to ensure that DMUs are only compared to DMUs with similar soil characteristics, and for given IDEA scores (ii) we perform a second stage analysis to account for external factors influencing the performance of DMU using OLS regression.

The input variables to the IDEA include nitrogen fertilizer (FTN) in kg/ha, and irrigation water (IRGA) in mm. Desirable outputs are crop yields (YLDD) in t/ha, dry matter straw yields (YLDS) in t/ha, and topsoil organic carbon stocks (OCPD) in t/ha. Undesirable outputs are total nitrogen emissions in kg/ha and soil sediment losses (MUST) in t/ha.

Our IDEA is performed by (i) tillage systems (minimum, conventional and reduced tillage), which we subsequently refer to IDEA model 3. It allows us to get detailed information on the efficiency for each tillage system and to stress the difference between the management option with and without straw removal. To verify the obtained results, an IDEA for (ii) all six tillage and straw management options (DEA model 6) is performed, as well as an IDEA for all (iii) soil texture classes. In the latter case, an efficiency frontier for each soil texture class is estimated which allows comparing tillage systems and also implicitly controls for the influence of soil textures on outputs.

Furthermore, a "vertical" IDEA has been performed comparing the performance of each crop management system on each DMU. It is in particular attractive, because all HRU characteristics are implicitly accounted for.

Finally, an IDEA model 3 with constant returns to scale has been performed to obtain information on scale inefficiencies.

Details on the partial relationships between dry matter crop and straw yields and the managements systems, soil classes, fertilization, irrigation and precipitation are given in the appendix (cp. Table 8).

5. Results of the efficiency analyses

The efficiency scores have been grouped into five classes for better presentation. The first class comprises technically efficient (TE) DMUs with value 0; the second class comprises DMUs which can improve their efficiency up to 20%; the third class comprises DMUs which can improve their efficiency between 20% and 40%; the fourth class comprises DMUs which can improve between 40% and 60%; and the last class comprises the least efficient DMUs, which performance could be improved more than 60% compared to the most efficient DMUs.

5.1. Technically efficient crop management systems

The results from 19110 DMUs per tillage system of the IDEA model 3 reveal that about 1.8% are rated as technically efficient for both minimum and reduced tillage, and 2% for conventional tillage.

In general, management systems with straw removal yield more technically efficient DMUs than management systems without straw removal (cp. Table 3). Management systems with straw removal yield less inefficient units (which can improve more than 60%) than management systems without straw removal. Consequently, additional positive output through straw removal outweighs likely negative environmental effects such as declining soil organic carbon sequestrations. However, straw removal may also lead to less nitrogen emissions and therefore to less negative outputs.

Table 3. The percentage of management systems with and without straw removal out of the number of all technically efficient rated DMUs for both IDEA model 3 and 6.

	IDEA model 3		IDEA model 6	
Tillage System	without straw removal	with straw removal	without straw removal	with straw removal
Minimum tillage	18.3	81.7	47.0	53.0
Conventional tillage	30.3	69.7	48.1	51.9
Reduced tillage	22.1	77.9	49.5	50.5

Table 4. Summary statistics for efficiency values for each tillage system estimated by IDEA model 3

	Minimum	1st Quintile	Median	Mean	3rd Quintile	maximum
Minimum without straw removal	0	0.2308	0.3295	0.3263	0.4215	0.7433
Minimum with straw removal	0	**0.1432**	**0.2433**	**0.2483**	**0.3413**	**0.7192**
Conventional without straw removal	0	0.2283	**0.3458**	**0.3361**	**0.4418**	**0.7516**
Conventional with straw removal	0	0.1594	0.2704	0.2699	0.3716	0.7335
Reduced without straw removal	0	**0.2331**	0.3386	0.3325	0.4324	0.7437
Reduced with straw removal	0	0.1548	0.2574	0.2595	0.3554	0.7264

Note: Lowest and highest values are in bold.

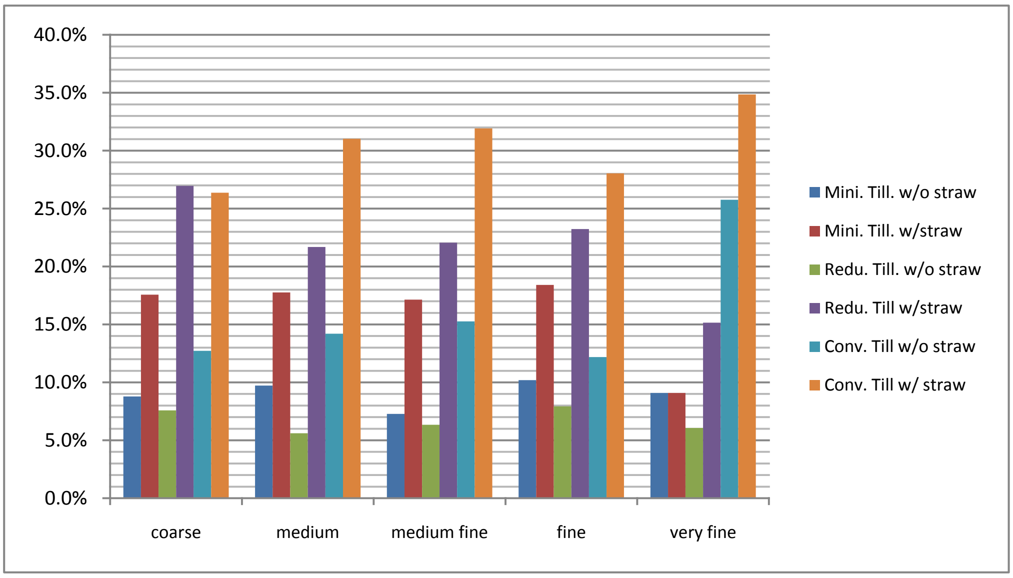
Table 4 provides a statistical summary of IDEA 3 results for all DMU. The mean values for tillage systems with straw removal are always lower than for systems without straw removal. Minimum tillage with straw removal has the lowest values, whereas conventional tillage without straw removal has the highest values. Hence, conventional tillage with straw removal has the most technically efficient rated DMUs. IDEA model 6 yields similar results.

Approximately 10 % of all technically efficient management systems exhibit scale inefficiencies. The percentages of scale inefficient management systems range from 7.5 % in conventional tillage systems with straw removal to 13.6 % in reduced tillage systems without straw removal. The summary statistics of technical efficiency scores under constant returns to scale shows lower efficiency values than in the case of variable returns to scale. It confirms that models under the variable returns to scale constraint yield more technical efficient rated crop management systems (cp. Table 9 in the appendix).

The “vertical” IDEA focuses on the question which of the six crop management system is rated efficient for each of the 9555 simulated cropland sites in EU25. The results show that also conventional tillage with straw removal is rated most often technically efficient (99.8%). It is followed by minimum tillage with straw removal with 92.5%, reduced tillage with straw removal with 87.5%, conventional tillage without straw removal with 87.2%, minimum tillage without straw removal with 45.8%, and reduced tillage without straw removal with 33.5%. This “vertical” IDEA model is in particular appealing, because the ecological characteristics of a simulation site are implicitly taken into account.

Another IDEA has been performed by soil texture classes (i.e. coarse, medium, medium fine, fine and very fine). Again, conventional tillage with straw removal has been rated most often technically efficient in all soil texture classes. This crop management system is followed by reduced tillage with straw removal and minimum tillage with straw removal. Only in the coarse soil texture class, reduced tillage systems with straw removal is most often rated technically efficient (cp. Figure 4). These results emphasize the differences in technical efficiency between crop management system with and without straw removal. The proportion of tillage systems without straw removal is increasing with inefficiency ratings and the proportion of tillage system with straw removal is increasing with efficiency ratings.

Figure 4. Percentages of technically efficient crop management systems per soil texture class



5.2. Geographical location of technically efficient crop management systems in EU25

The geographical presentations of results from IDEA model 3 are illustrated in six maps which can be found in the appendix of this article. Overall, 12 regional “efficiency clusters” can be identified. These clusters consist of DMUs which are rated technically efficient for each of the three tillage systems and include: 1 NUTS2 region in the Czech Republic, 6 NUTS2 regions in

Germany, 1 NUTS2 region in Denmark, 4 NUTS2 regions Spain, 2 NUTS2 regions in Finland, 3 NUTS2 regions France, 1 NUTS2 region in Hungary, 2 NUTS2 regions in Italy 1 NUTS2 region in the Netherlands, 3 NUTS2 regions in Poland, 3 NUTS2 regions in Sweden, and 5 NUTS2 regions in the United Kingdom.

These regions mainly consist of medium soil texture and include the cultivation of winter wheat and spring barley. As will be shown in the following subsections, these properties are characteristics for technically efficient DMUs.

Some of these ratings might seem surprising as they are based in Finland, Sweden, or the United Kingdom, where site conditions for crop production are not always favorable. It should be kept in mind that efficiencies are evaluated for the entire crop rotation system and fertilization rates are adjusted to average crop yields in the NUTS2 region. The efficiency ranking emphasizes which crop rotation system is best adjusted to the environmental conditions and management systems. Also several regions which are found in the technically most inefficient class for each of the three tillage option have been identified: 1 NUTS2 region in Austria, 1 NUTS2 region in France, 4 NUTS2 regions in Greece, 3 NUTS2 region in Italy, 3 NUTS2 region in Portugal, 2 NUTS2 region in United Kingdom. Except from the United Kingdom, these regions are found mainly in the south of Europe. Consistent with the analysis in the following subsections, the crop rotation systems of these inefficient regions mainly include corn and grass clover mixes and are found on medium and coarse soil textures. The spatially explicit efficiency distributions over EU25 are depicted in three maps in the appendix (cp. Figure 9, 10, and 11).

5.3. Distribution of crops in technically efficient crop management systems

The efficiency analysis is based on average crop yields and environmental outputs per crop rotation system and crop management system. Therefore, the question emerges which crops are included in technically efficient crop management systems? The distribution of crops in most and least efficient crop management systems are shown in Figure 5 to 7. Referring to the efficiency results of the IDEA model 3, following directions for the distribution of crops in the technically efficient rated DMUs can be observed. Similar to the distribution of crops, summer barley and winter wheat have the highest proportion in technically efficient rated DMUs for all tillage systems, followed by oats, sugar beets field pea, corn silage and corn. In the least efficient class are crops like corn, durum wheat and grass clover mix.

Figure 5. Distribution of crops in technically efficient crop management systems

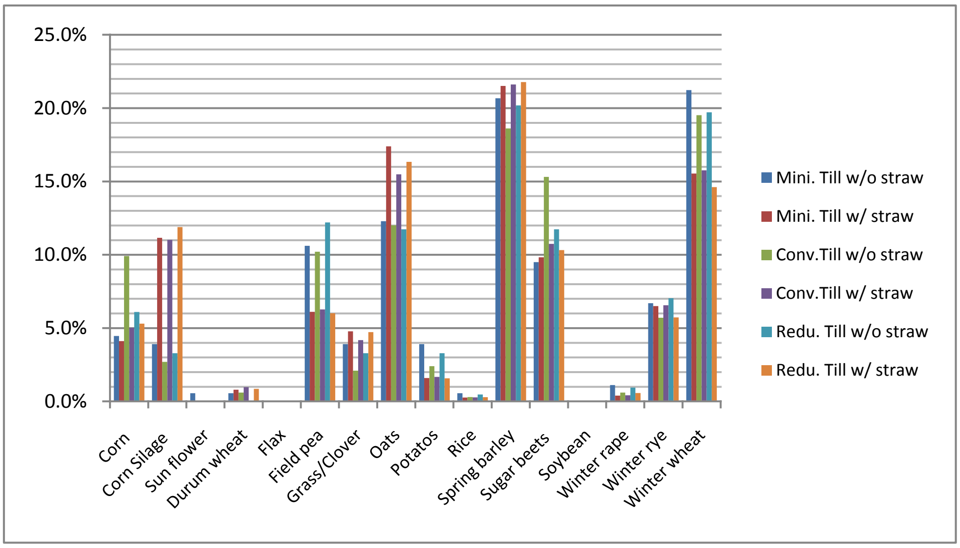
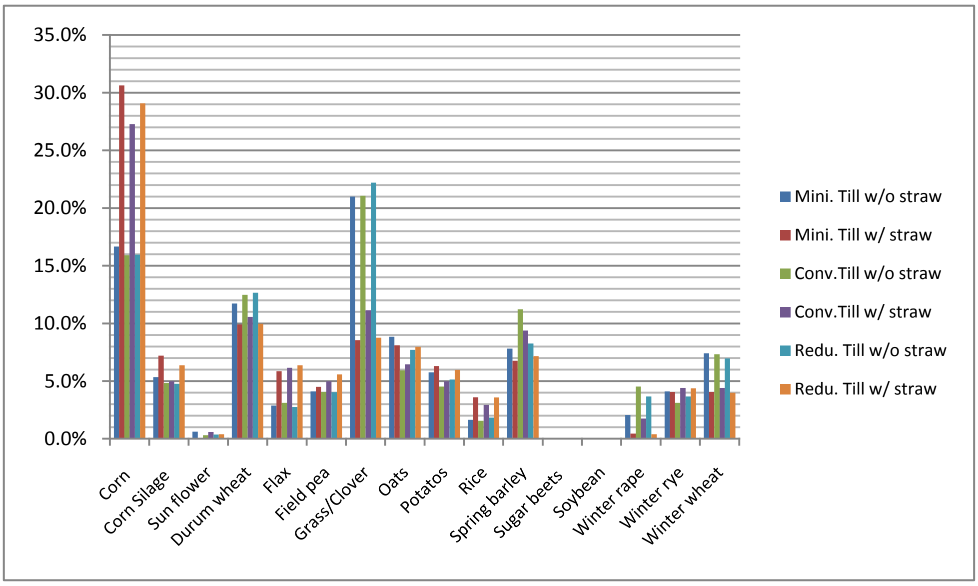
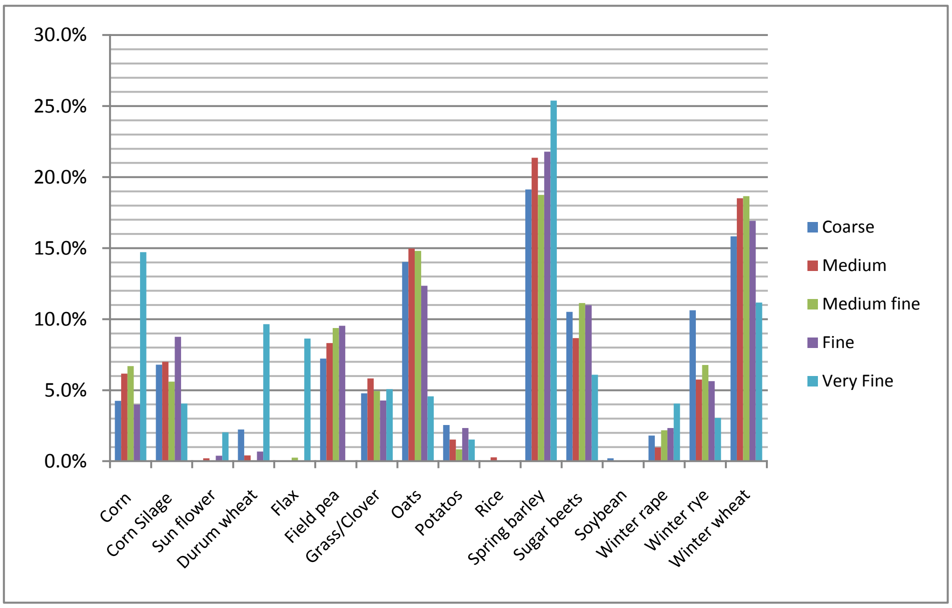


Figure 6. Distribution of crops in the least technically efficient crop management systems



The efficiency analysis by soil texture classes has similar results regarding the composition of crops in technically efficient rated DMUs. Summer barley, followed by winter wheat and oats are most often found in technically efficient rated DMUs (cp. Figure 7)

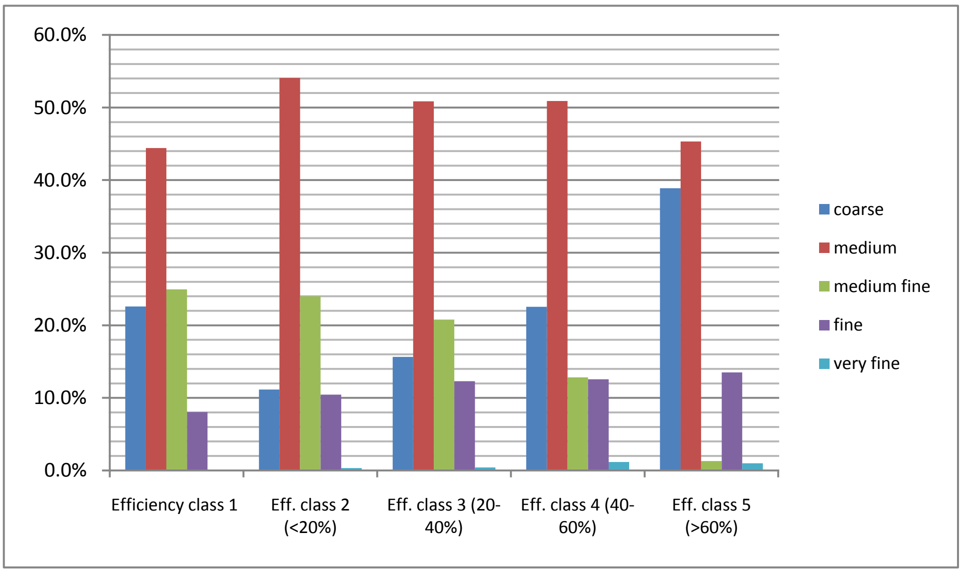
Figure 7. Distribution of crops in technically efficient DMUs per soil texture class



5.4.Distribution of soil texture classes over technical efficiency classes

Similar to the question which crops are found in the technically efficient rated crop management systems, the question arises on which soil types technical efficient crop management systems are found most often as well as least efficient crop management systems. We use results from IDEA model 3, which evaluates efficiencies for each tillage system separately.

Figure 8. Distribution of soil texture classes in various efficiency classes.



Notes: Efficiency class 1 comprises only DMUs which are rated technically efficient; Eff.class 2 (20%) includes DMUs for which outputs can be improved by 20%; Eff.class 3 (20-40%) includes DMUs for which outputs can be improved between 20-40%; Eff.class 4 (40-60%) includes DMUs for which outputs can be improved between 40-60%; Eff.class 5 (>60%) includes DMUs for which outputs can be improved between for more than 60%.

Medium soil texture appears with the highest frequency in the sample and in all efficiency classes (cp. Figure 8). The focus should rather be on medium fine and coarse soil texture classes, which occur in more or less equal frequency in the sample: the proportion of the coarse soil texture class increases with increasing inefficiency results. Similarly the proportion of the fine soil texture class increases with increasing inefficiency, whereas the proportion of the medium fine soil texture class increases with increasing efficiency (cp. Figure 8).

5.5. Analyzing environmental factors influencing efficiency results

The question which external factors influence efficiency ratings is investigated in this subsection. The efficiency results are taken from the analysis per tillage (IDEA model 3). External factors such as soil texture, precipitation and slope steepness characterize a DMU and are not dependent on the management system. We apply an OLS model, because the percentage of technically efficient management systems is rather low (e.g. the percentage of technical efficient rated management systems out of 19110 DMU is 2 % for conventional tillage, and 1.8 % for minimum and reduced tillage, respectively). Technical efficiencies of all tillage systems are regressed against these external factors. The regression separated by tillage system yields nearly the same results.

Table 5. OLS Regression analysis on efficiency ratings

	Coefficients	Std. Err.	t-value	P>|t|	95% Conf.	Interval
Soil class medium	-0.0431471	0.0017251	-25.01	0.000	-0.0465283	-0.0397659
Soil class medium fine	-0.0743596	0.0019268	-38.59	0.000	-0.0781362	-0.070583
Soil class fine	-0.0155448	0.0022896	-6.79	0.000	-0.0200324	-0.0110572
Soil class very fine	0.0545974	0.0074935	7.29	0.000	0.0399102	0.0692846
slope class 3-6 %	0.0188454	0.0014036	13.43	0.000	0.0160945	0.0215964
slope class 6-10 %	0.0281404	0.0016395	17.16	0.000	0.0249269	0.0313539
slope class 10-15 %	0.0382565	0.0022155	17.27	0.000	0.0339141	0.0425988
slope class 15-30 %	0.0494447	0.0032194	15.36	0.000	0.0431346	0.0557547
slope class 30-50 %	0.0229701	0.0078355	2.93	0.003	0.0076124	0.0383278
slope class >50 %	0.1220114	0.0207792	5.87	0.000	0.0812841	0.1627388
Precip. class 500-700mm	0.0559202	0.0019026	29.39	0.000	0.0521911	0.0596493
Precip. class 700-1000mm	0.1148883	0.0019709	58.29	0.000	0.1110254	0.1187513
Precip. class > 1100mm	0.1169246	0.0025981	45	0.000	0.1118323	0.1220169

Number of observations 57330
F(13, 57316) 558.97; Prob > F = 0.0000
R-squared 0.1095
Root MSE 0.13855
Residuals: Min: 0.1655488 Mean: 0.2954405; Max: 0.4788444; Stand. Err.: 0.0485758

The reference site characteristics are coarse soil texture, slope class < 3 % and precipitation < 500 mm. All coefficients are statistically significant on the highest level, except the coefficients for slope classes 30-50% which is significant at 10% and > 50% which is significant at 1%.

Compared to the coarse soil texture class, medium fine, medium and fine soil texture classes have an improving effect on the efficiency ratings. These results confirm previous findings (cp. subsection 5.4) that most efficiency ratings are found in the medium fine soil texture class. The statistically significant coefficients of increasing slopes have, as expected, a negative impact on efficiency ratings. Also the coefficients for precipitation classes are statistically significant. Their signs are positive which implies that increasing precipitation (>500 mm) has a decreasing effect on the efficiency ratings.

A linear correlation coefficient and the Spearman rank correlation are calculated to analyze the relationships between IDEA inputs and outputs and the size of efficiency scores. Since best practice DMUs take an efficiency value of 0, a negative correlation coefficient indicates that the respective input is correlated with increasing efficiency scores. Table 6 lists the correlation coefficients per crop management system.

Table 6. Correlation Coefficients between values of technical efficiency and IDEA inputs and outputs per crop management system.

Technical efficiency measures	YLDD	YLDS	FTN	IRGA	OCPD	MUST	N emission
Correlation coefficients							
all tillage systems	**-0.398**	-0.096	0.116	-0.165	-0.112	0.110	0.076
Minimum tillage w/o straw removal	**-0.428**	0.223	0.179	-0.174	-0.113	0.183	0.115
Minimum tillage w/ straw removal	**-0.364**	-0.148	0.086	-0.175	-0.110	0.100	0.084
Conventional tillage w/o straw removal	**-0.459**	0.135	0.158	-0.175	-0.101	0.111	0.078
Conventional tillage w/ straw removal	**-0.396**	-0.187	0.065	-0.161	-0.137	0.065	0.030
Reduced tillage w/o straw removal	**-0.441**	0.178	0.162	-0.173	-0.117	0.163	0.096
Reduced tillage w/ straw removal	**-0.376**	-0.161	0.073	-0.167	-0.128	0.098	0.066
Spearman correlation coefficients							
All tillage systems	**-0.351**	-0.019	0.134	-0.176	-0.035	0.242	0.256
Minimum tillage w/o straw removal	**-0.374**	0.312	0.196	-0.194	-0.010	0.338	0.343
Minimum tillage w/ straw removal	**-0.317**	-0.090	0.110	-0.185	0.033	-0.232	0.258
Conventional tillage w/o straw removal	**-0.405**	0.249	0.175	-0.187	-0.012	0.243	0.280
Conventional tillage w/ straw removal	**-0.354**	-0.129	0.085	-0.169	-0.074	0.192	0.180
Reduced tillage w/o straw removal	**-0.386**	0.281	0.178	-0.189	-0.023	0.309	0.311
Reduced tillage w/ straw removal	**-0.329**	-0.100	0.096	-0.176	-0.058	0.227	0.235

Legend: YLDD: dry matter crop yield; YLDS: dry matter straw yield; FTN: Nitrogen fertilizer; IRGA: irrigation; MUST: soil sediment losses; OCPD: topsoil organic carbon stocks; N emission: Nitrogen emission

Note: highest correlation indicated in bold

In general, similar signs and magnitudes can be observed between both correlation coefficients. Dry matter crop yield (YLDD) shows the highest correlation with high technical efficiency scores, particularly for tillage systems without straw removal. As expected, the correlation of dry matter straw yields (YLDS) with efficiency scores of management systems without straw removal is correlated positively with efficiency scores of tillage systems without straw removal and a negatively with tillage system with straw removal. Nitrogen fertilizer (FTN) is correlated positively with increasing inefficiency results. The amount of irrigation is positively correlated with increasing efficiency results and exhibits a rather equal correlation over all management systems. Topsoil organic carbon (OCPD) is also correlated with increasing efficiency. However, the Spearman correlation coefficient yields only very low correlations for OCPD and thereby yields a higher correlation for management systems without straw removal.

The undesirable outputs of the IDEA model, nitrogen emissions (N emission) and soil sediment losses (MUST) are higher correlated with efficiency scores under the Spearman correlation index than under the linear correlation index. The signs of correlation coefficients are positive implying that values of MUST and N emission are correlated with low efficiency scores. There is only one irregularity with sediment transport (MUST), which is minimum tillage, where MUST actually is negative, such that there is a positive correlation between soil erosion and good efficiency values. For conventional and reduced tillage the correlation is higher in cases without straw removal.

6. Conclusions

A non-parametric Integrated Data Envelopment Analysis (IDEA) method is used to provide a single efficiency measure for alternative crop management systems. The aim of this analysis is to show which crop management systems are rated as technically efficient in the spatial context of EU25. In the course of this analysis we expanded the traditional DEA model to include undesirable agricultural outputs like agricultural emission and soil sediment losses towards an environmentally integrated DEA (IDEA). In determining technical efficiencies of crop management systems, we consider in our IDEA site characteristics such as soil texture, climate, slope and elevation as well as crop management systems such as crop rotations, tillage, and fertilization and irrigation. Furthermore, we analyze IDEA inputs and outputs with respect to their influence on efficiency scores. We have also performed several IDEA models by controlling for crop management systems or site characteristics to better identify efficient crop management systems in the spatial context of EU25. All positive and negative outputs for IDEA have been simulated with the bio-physical process model EPIC.

The IDEA results show that crop management systems with straw removal have more and higher efficiency ratings than management systems without straw removal. DMUs with high efficiency ratings usually include spring barley, winter wheat and oats in their crop rotation systems; whereas DMUs in the least efficiency class include corn, durum wheat and grass clover mixes. Most technically efficient crop production units are found on medium soil texture classes. However, we found that the proportion of the coarse soil texture class is increasing with increasing inefficiency, whereas the proportion of the medium fine soil texture class is increasing with increasing efficiency. Also the proportion of the very fine soil texture class is increasing with in increasing inefficiency. An OLS regression is performed with the IDEA inputs and outputs on the efficiency results. This regression confirms that soil texture classes medium, medium fine and fine are correlated with higher efficiency scores than coarse soil, and that increasing slope percentages are positively correlated with decreasing efficiency results. The coefficients for increasing precipitation classes are equally increasing with increasing inefficiency.

An EU25 comparison of technically efficient DMU shows that least inefficiency DMUs are usually located in the South of Europe (Portugal, Greece, Corse or Italy), and most efficient DMU are mainly located in Central and Northern Europe. Even though some of the technically efficient rated regions, like Finland or Sweden seem surprising, because their climatic conditions do not quite favor crop production, it has to be kept in mind that the IDEA is based on the average crop yield of crop rotation systems, such that the efficiency rating highlights which crop rotation system is best adjusted to the environmental and management conditions in a specific region relative to other crop rotation systems in other regions.

7. References

Banker R.D. and Morey R.C. (1986). Efficiency Analysis for Exogenously Fixed Inputs and Outputs. Operations Research 34 (4), 513-521

Bradley, S., Johnes, J. and Little, A. (2006). The measurement and determinants of efficiency and productivity in the FE sector in England. Working Paper, Lancaster University Management School, Centre for Excellence in Leadership.

Bruinsma, J. (ed.) (2003): World agriculture: towards 2015/2030. An FAO Perspective. London: Earthscan Publications Ltd.

Cantner, U., Krüger J. and Hanusch, H. (2007) Produktivitäts- und Effizienzanalyse. Berlin Heidelberg New York: Springer

Chung, Y.H., Färe, R. and Grosskopf, S. (1997). Productivity and undesirable outputs: A Directional Distance Function Approach. Journal of Environmental Management 51, 229-240

Coelli, T., Rao, P. and Battsee, G. (2000). Introduction to Efficiency and Productivity Analysis. Boston, Dordrecht, London: Kluwer Academic Publishers. 4th printing

Cook W. and Seiford L.M. (2009). Data envelopment analysis (DEA) – Thirty years on, European Journal of Operational Research 192, 1–17

Cooper, W.W., Seiford, L.M. and Zhu, J. (2004). Data Envelopment Analysis: History, Models and Interpretations, in Cooper W.W., Seiford, L.M. and Zhu J. (eds.) Handbook on Data Envelopment Analysis, Chapter 1, 1-39, Boston: Kluwer Academic Publishers

FAO (2002). World agriculture: towards 2015-2030. Summary Report. Rome

Färe, R. and Grosskopf, S. (2004). Modeling Undesirable Factors in Efficiency Evaluation: Comment. European Journal of Operational Research 157, 242-245

Foley, J.A., Monfreda, C., Ramankutty, N. and Zaks, D. (2007). Our share of the planetary pie. PNAS 104 (31), 12585–12586.

Fox, J.E., Gulledge, J., Engelhaupt, E., Burow, M.E. and McLachlan, J.A. (2007). Pesticides reduce symbiotic efficiency of nitrogen-fixing rhizobia and host plants. PNAS 104 (24), 10282–10287.

Hussain, I. and Hanjra, M.A., 2003. Does irrigation water matter for rural poverty alleviation? Evidence from South and South-East Asia. Water Policy, 5 (5), 429–442.

Hussain, I. and Hanjra, M.A., 2004. Irrigation and poverty alleviation: review of the empirical evidence. Irrigation and Drainage 53 (1), 1–15.

Hoff, A. (2007). Second stage DEA: Comparison of approaches for modelling the DEA score. European Journal of Operational Research 181, 425–435

Khan, S. and Hanjra, M. (2009). “Footprints of water and energy inputs in food production – Global perspectives” Food Policy, 34 (2), 130-140

Lovell, C.A.K. (1993). Production frontiers and productive efficiency. In Fried, H.O., Lovell, C.A.K. and Schmidt, S.S. (eds.). The Measurement of Productive efficiency. Oxford. Oxford University Press.

Macauley, M (2006). The value of information: Measuring the contribution of space-derived earth science data to resource management. Space Policy 22, 274–282

McDonald, J. (2009). Using least squares and tobit in second stage DEA efficiency analyses. European Journal of Operational Research 197, 792–798

Regmi, A., Takeshima H. and Unnevehr, L. (2008). “Convergence in Global Food Demand and Delivery”, USDA Economic Research Service, Economic Research Report Number 56

Skalský, R., Tarasovičová, Z., Balkovič J., Schmid E., Fuchs M., Moltchanova E., Kindermann, G., and Scholtz, P. (2008). GEO-BENE global database for bio-physical modeling v. 1.0 (Concepts, methodologies and data). Available on http://www.geo-bene.eu/files/Deliverables/Geo-BeneGlbDb10(DataDescription).pdf; April 2009

Trostle, R. (2008). Global Agricultural Supply and Demand: factors contributing to the Recent Increase in Food Commodity Prices, USDA WRS-0801

Watson, R. (2005).”Turning science into policy: challenges and experiences from the science policy interface”. Philos Trans R Soc London B Biol Sci 360, 1454: 471-477

Yang, H. and Pollitt, M (2009). Incorporating both undesirable outputs and uncontrollable variables into DEA: The performance of Chinese coal-fired power plants. European Journal of Operational Research 197, 1095-1105

APPENDIX

Table 7. Data for EPIC simulations at EU25 scale

Group	Data Set	Description
Climate	MARS	Monitoring of Agriculture with Remote Sensing (50 km)
	EAST ANGLIA	Tyndall Center for Climate Change Research (0.5°)
	EMEP	Monitoring and evaluation of the long- range transmission of air pollution in Europe (50km)
Soil	ESDB v.2	The European soil database v.2. (10km, 1km)
	OC TOP v. 1.2	The map of Organic Carbon in the Topsoil in Europe, Ver. 1.2
	HYPRESE	Hydraulic Properties of European Soils, (PTF Data)
Topography	GTOPO30	Global digital elevation model (30 arc seconds)
Land Cover	CORINE/PELCOM	Combined CORINE and PELCOM (1 km)
Admin. Region	AGISCO	Geographic Information system of European Commission data

Reference grid	SWU	JSR Soil and Waste Unit reference grid (10k)
Agricultural statistics	NEW CRONOS	New Cronos Regional Statistics (NUTS2, NUTS1)
	LUCAS	Land use and land cover area frame statistical survey project data (Phase I.)
	MARS	Monitoring of Agriculture with remote Sensing (50 km)

Table 8**.** OLS regression on the sum of dry matter crop and straw yield by tillage systems, soil classes, irrigation, nitrogen fertilization, nitrogen emission and precipitation classes.

YIELD	Coef.	Std. Err.	T	P>|t|	[95% Conf.	Interval]
(intercept)	0.603	0.029	20.960	0.000	0.547	0.660
minimum tillage	-0.209	0.015	-14.270	0.000	-0.238	-0.180
reduced tillage	-0.070	0.015	-4.800	0.000	-0.099	-0.042
soil classe medium	0.287	0.017	16.960	0.000	0.254	0.320
soil classe medium fine	0.426	0.020	21.230	0.000	0.387	0.465
soil classe fine	0.105	0.023	4.610	0.000	0.061	0.150
soil classe very fine	-0.816	0.080	-10.180	0.000	-0.973	-0.659
irrigation	0.007	0.000	43.900	0.000	0.007	0.007
nitrate fertilization	0.027	0.000	163.880	0.000	0.026	0.027
N emission	0.002	0.000	31.220	0.000	0.002	0.002
Precip. class (500-700mm)	0.632	0.021	29.840	0.000	0.590	0.673
Precip. class (700-900mm)	0.641	0.023	28.370	0.000	0.596	0.685
Precip. class (900-1100mm)	1.135	0.028	40.370	0.000	1.080	1.190
Precip. class (1100-1300mm)	0.536	0.037	14.450	0.000	0.463	0.608
Precip. class (1300-2800mm)	0.263	0.046	5.720	0.000	0.173	0.353

Number of obs = 57328
F(14, 57313) = 3303.54 Prob > F = 0.0000
R-squared = 0.4466
Adj R-squared = 0.4465
Root MSE = 1.4281
Residuals: Min: -6.852169; Median: 1.427958 , Max: 7.584356, Stand.Err.: -.1092085

Notes: Tillage systems, soil texture classes and precipitation classes are integrated as qualitative variables. The reference values for the respective coefficients are conventional tillage, coarse soil class texture and precipitation class < 500mm.

Table 9. Summary statistics of technical efficiency scores under constant returns to scale

	Min.	1st quintile	Median	Mean	3rd quintile	Max.
Minimum tillage w/o straw removal	0	0.2395	0.3425	0.3414	0.4417	0.7633
Minimum tillage w/ straw removal	0	**0.1548**	**0.267**	**0.2697**	**0.3748**	**0.745**
Conventional tillage w/o straw removal	0	0.2404	0.3635	0.3524	0.4637	0.7786
Conventional tillage w/ straw removal	0	0.1757	0.2963	0.2936	0.4086	0.7509
Reduced tillage w/o straw removal	0	0.2425	0.3514	0.3468	0.4506	0.7701
Reduced tillage w/ straw removal	0	0.1664	0.2796	0.28	0.3874	0.7474

Figure 9. Distribution of efficiency scores when applying conventional tillage system with and without straw removal on croplands in EU25

Conventional tillage without straw removal | Conventional tillage with straw removal

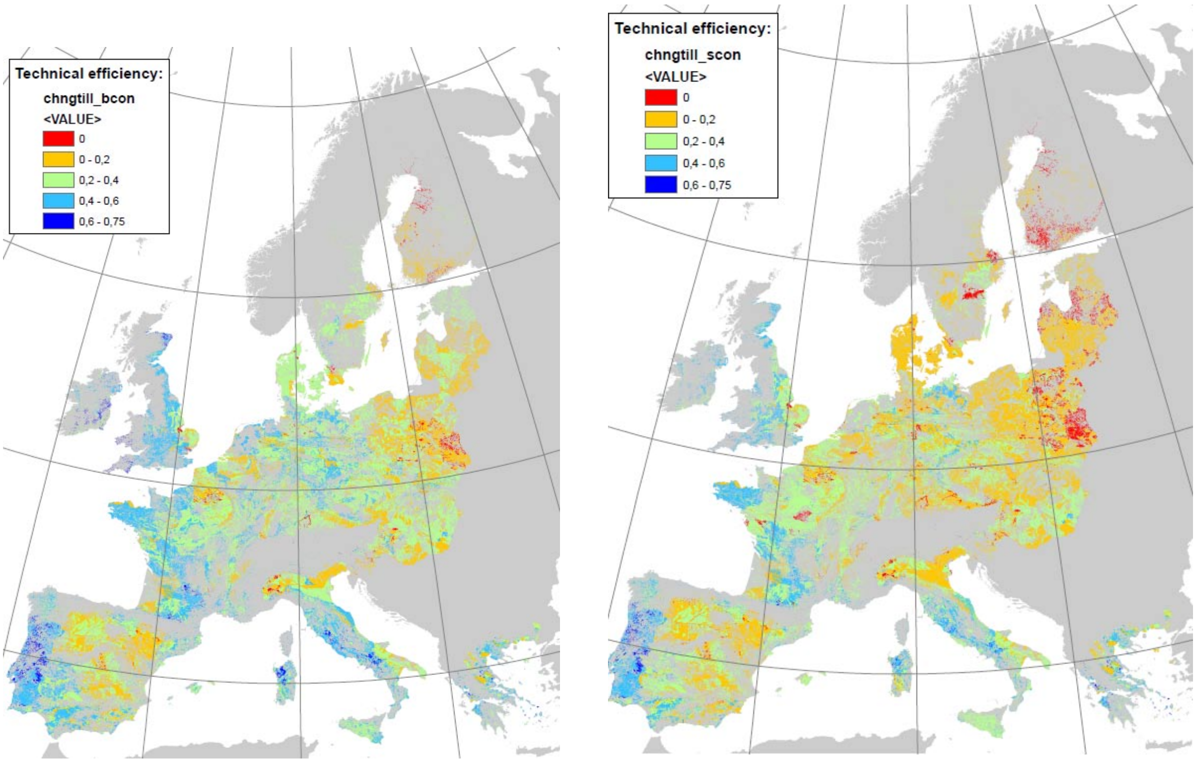


Figure 10. Distribution of efficiency scores when applying minimum tillage system with and without straw removal on croplands in EU25

Minimum tillage without straw removal | Minimum tillage with straw removal

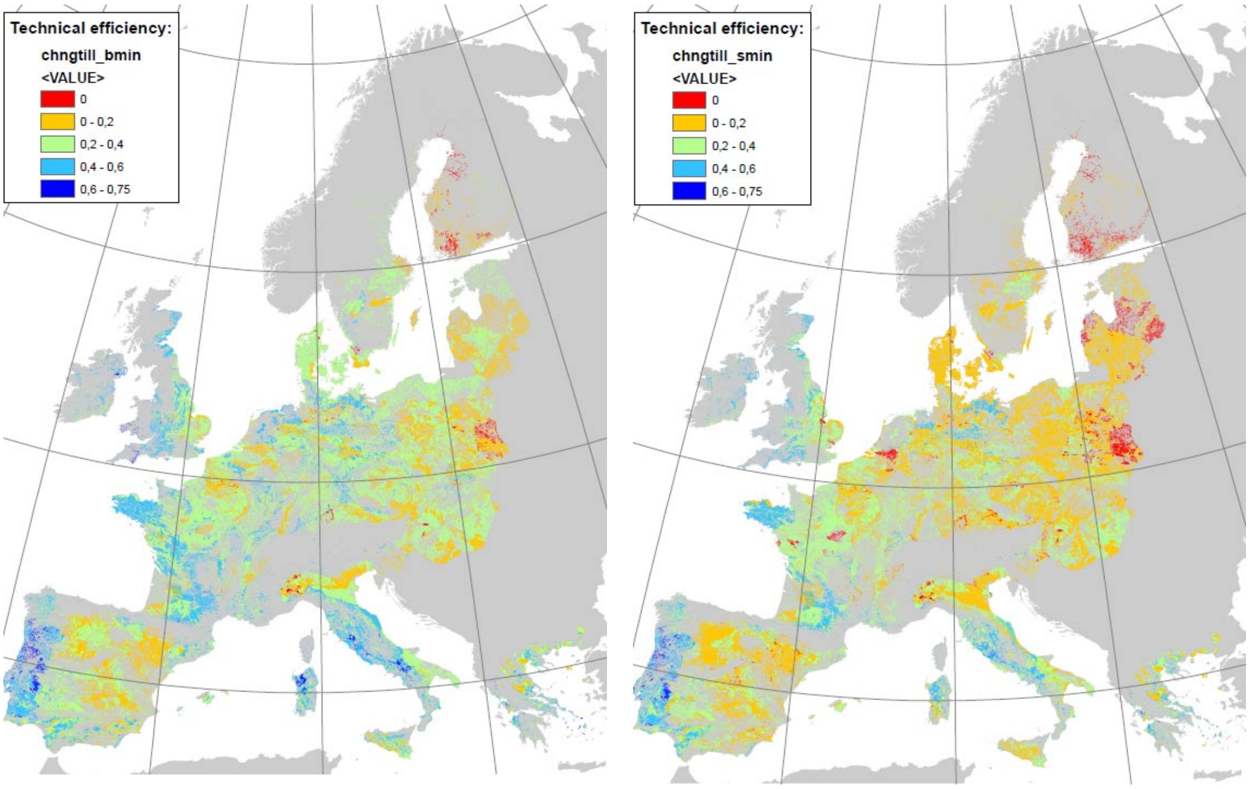
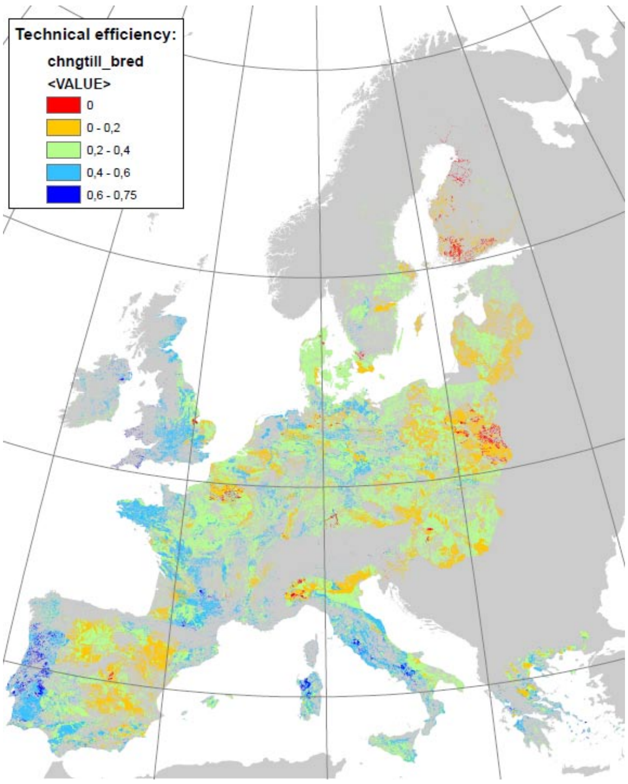
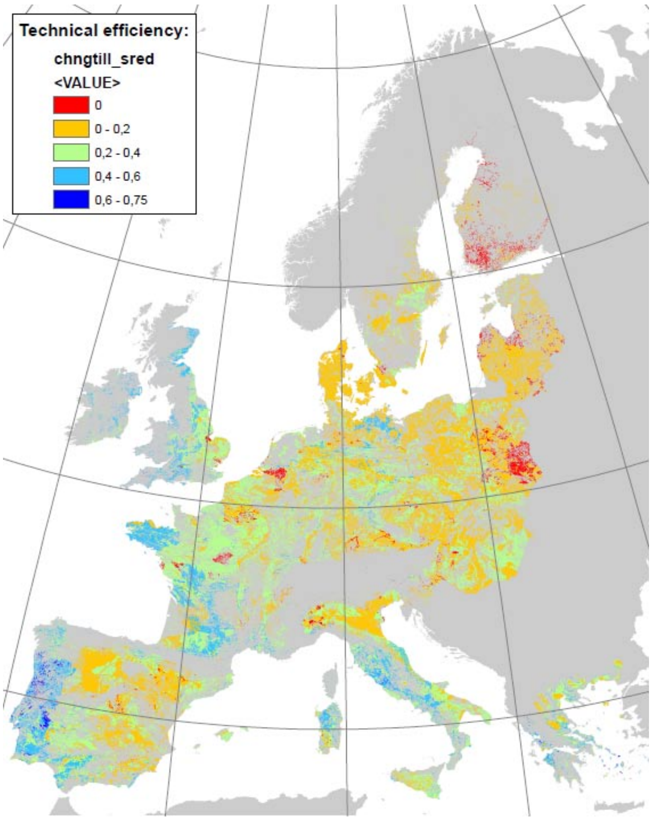


Figure 11. Distribution of efficiency scores when applying reduced tillage system with and without straw removal on croplands in EU25

Reduced tillage without straw removal



Reduced tillage with straw removal



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Agricultural land use changes in Eiderstedt: historic developments and future plans

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Abstract

The Eiderstedt peninsula in Schleswig-Holstein (Germany) has a long tradition as agricultural land. In the past, the landscape has been generally dominated by extensively used grassland. These grassland areas are home to many bird species, so that Eiderstedt can be considered to be one of the most important bird habitats in Schleswig-Holstein. Ongoing changes in the structure of the regional agriculture towards an intensified dairy production and the growth of biofuels call for a conversion of large shares of grassland to arable farm land. However, these plans are fiercely debated because a strong decline in grassland area is likely to have a considerable ecological impact on domestic meadowbird species. In this study, these problems accompanying an extensive land use change on Eiderstedt are explored. Three possible scenarios of transformations of agricultural land are developed which can be applied to determine the possible impacts of such conversions.

1 Ecological implications of land use choices on Eiderstedt

The peninsula Eiderstedt at the West coast of Schleswig-Holstein is a region that is traditionally mainly used agriculturally. The dominant agricultural land use options are extensive management of grassland and the production of crops on arable farm land. Historically, there have been distinct shifts in the shares of these two land use options, each altering the characteristics of the landscape of Eiderstedt considerably. In times when the focus of agricultural activities on Eiderstedt was on the export of cattle as was the case in the late 19th century (Hammerich 1984), practically all agricultural land on Eiderstedt was used as grassland (LVermA-SH 2007a). But there were also periods in which more than half of the land was arable farm land.

These shifts in land use have ecological implications as Eiderstedt is considered to be one of the prime habitats for meadowbirds in Germany (Hötker et al. 2005) breeding in the large grassland and wetland areas adjacent to the North Sea. In addition, vast amounts of migrating birds pass through Eiderstedt in spring on their way from wintering grounds in the South to Scandinavia as well as on their way back in fall. The Naturschutzbund Deutschland (NABU) classifies Eiderstedt as wetland region of international importance based on the Ramsar convention (NABU 2005). Most of the bird species breeding on Eiderstedt prefer extensively used grassland or wetlands as breeding habitat, while arable farm land is much less suitable for the rearing of offspring.

Currently, approximately three quarters of the agricultural land on Eiderstedt is used as grassland (Stat A Nord 2004). However, plans to increase the share of arable farm land drastically in order to adapt to changes in agricultural production patterns are discussed. Altered boundary conditions brought about by changes in European agricultural policy often necessitate the switch from outdoor dairy production to maintaining the cattle stocks in stables (Nehls 2002). This means that crops with higher energy content have to be fed, which must grow on arable farm land in the vicinity. These kinds of land use change are generally irreversible as arable farm land on Eiderstedt needs to be artificially drained so that the original ponds that are characteristic for the landscape in this region are destroyed during the conversion process. According to the local farmers union, two thirds of the agricultural land on Eiderstedt are supposed to be converted to arable farm land within the next couple of decades (NABU 2004). Such a change would not only distinctly alter the appearance of Eiderstedt, but would also mean the loss of valuable bird habitats and possibly a reduction of the recreational attractiveness of the landscape to visitors.

This study will look at possible scenarios of land use development on the Eiderstedt peninsula. After a brief historic overview of past agricultural land use changes in this region, the controversy between farmers and environmentalists about the future development of the local agriculture is presented. Using a geographic information system (GIS), scenarios of a future conversion of grassland to arable farm land on Eiderstedt are developed and described. These scenarios can be used in further assessments to quantify the ecological impacts of each development path.

2 Historic development of agricultural land use in Eiderstedt

Eiderstedt is a peninsula at the West coast of Schleswig-Holstein that extends into the North Sea. It is located between the river Eider in the South and the town of Husum in the Northeast. Back in the 11th century, Eiderstedt consisted of several geest islands, but started to grow together as a consequence of the first coastal protection measures being erected at that time (Meier 2001). Initially, transportation was only possible by boat as settlements were exclusively accessible from the North Sea. These waterways remained in operation for several centuries and its underlying pattern is still recognizable. Today, almost the entire peninsula is enclosed by dikes built to withstand severe storm floods. This makes it necessary to artificially drain the land area. Parallel passing drills (in German: Grüppen) have been constructed that have become a typical feature of the Eiderstedt landscape (Fischer 1997).

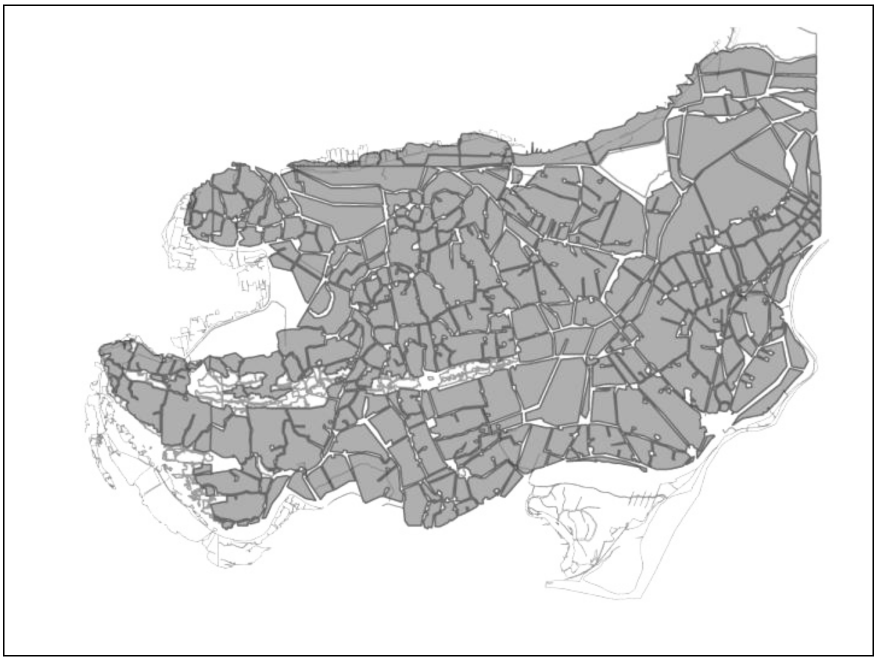

Figure 1: Agricultural land use on the Eiderstedt peninsula in 1878, grassland is shown in dark grey and arable farm land in light grey (based on LVermA-SH 2007a)

The soil quality of the marshland is quite high (Feddersen 1853; InfoNet Umwelt 2007). In the early 19th century crop production was of great importance on Eiderstedt (Hammerich 1984) and the share of arable farm land was quite high. In some years close to half of the agricultural land was used to grow crops. In the middle of that century cattle farming became the prime means of agricultural production as exports of cattle to the United Kingdom via the harbors of Tönning and Husum were very profitable. Consequently, meadows and grassland with ponds and drainage drills running through became the dominant type of agricultural land on Eiderstedt. When detailed maps of Germany were drawn up by the Prussian government in the late 1870s, almost 93 % of the agricultural land consisted of grassland (LVermA-SH 2007a). Arable farm land was hardly found (Fig. 1): crop production took place only in the vicinity of the town of Garding and in the Northeast of Eiderstedt.

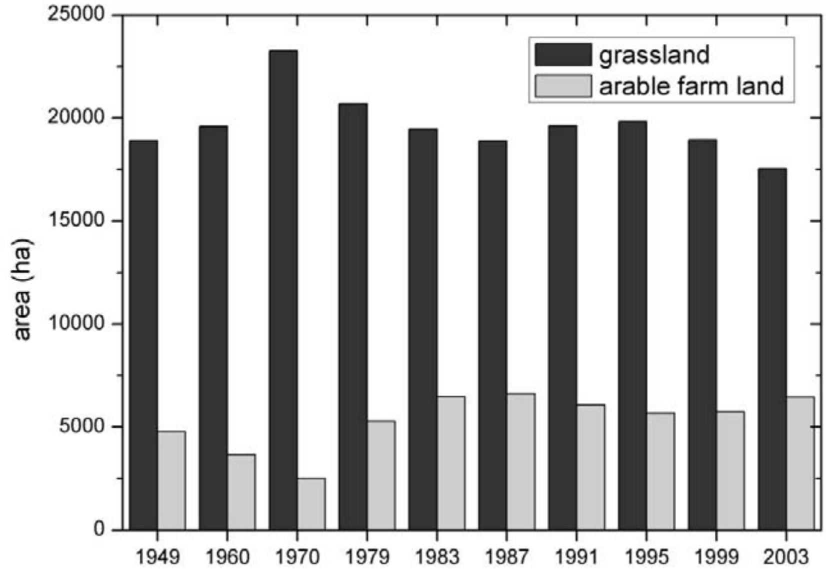

Figure 2: Distribution of agricultural land on Eiderstedt: grassland and arable farm land (based on Stat A Nord 1950-2004)

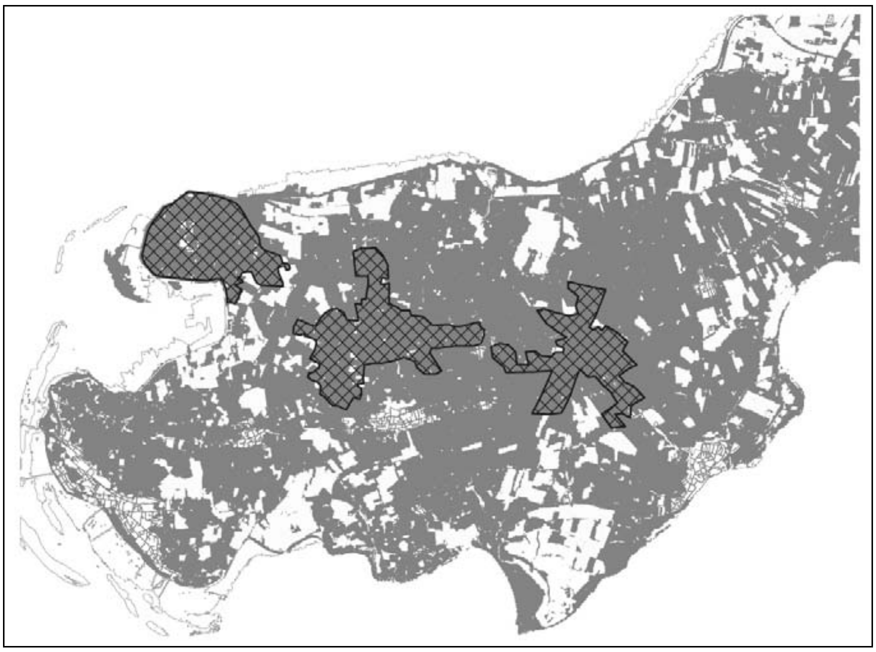

Figure 3: Agricultural land use on the Eiderstedt peninsula in 2002, grassland is shown in dark grey and arable farm land in light grey (based on LVermA-SH 2007b)

During the first half of the 20th century, there were only little changes in the distribution of agricultural land (Hammerich 1984) with the share of grassland always exceeding 80 %. After World War II the dairy production became dominant on Eiderstedt, which led to a further reduction of arable farm land until 1970 (Stat A Nord 1950-2004). Figure 2 shows that arable farm land started to increase afterwards, which was mainly due to an expansion of crop production on polders that were secured by dikes in the 1960s. Until 2003 the share of arable farm land remained stable at about one quarter of the total agricultural land. The distribution of the two dominant agricultural land uses in 2002 is illustrated in Figure 3, in which the three bird sanctuaries on Eiderstedt (Westerhever, Poppenbüll, and Kotzenbüll) are particularly marked. Even though crops are grown in all regions of Eiderstedt, there are vast areas of contiguous grassland, particularly in central Eiderstedt (LVermA-SH 2007b). These are of great ornithological significance.

In recent years, however, altered political boundary conditions have caused farmers to switch from dairy production with the extensive grassland use to higher intensity cattle farming and biofuels production. As intensive cattle farming involves permanent housing of the cattle, it is essential to grow the high energy forage crops. The increased demand for these crops and for those used in biofuel production necessitates an expansion of the share of arable farm land at the expense of grassland and meadows.

3 The controversy about plans for future land use change

Meadows and grassland are habitats with the potentially highest biodiversity in central Europe (Nehls 2002). They are threatened by an intensive agricultural use involving the application of large amounts of fertilizers, the conversion to arable farm land, and dehydration by improving drainage. A conversion of grassland to arable farm land destroys the diverse flora and fauna and cause a deterioration of the quality of the entire ecosystem. The expansion of grassland in other regions to offset the losses is inadequate as newly seeded grassland is ecologically worthless for a long period of time. Consequently, the plan to convert a significant share of the grassland on Eiderstedt to arable farm land is strictly opposed by environmental interest groups led by the NABU.

Farmers argue that protection plans proposed by NABU are far too restrictive and do not fare well with the economic necessities of the region. Their interest group Pro-Eiderstedt proposes contractual nature conservation, as conservation measures can only be realized in consent with the local farmers. Many such contracts were established in the late 1980s but their number declined in the 1990s when fundamental enforcement rules changed. In 2001, approximately 1 000 ha of agricultural land were managed by contractual conservation. According to the Ministry of Agriculture in Schleswig-Holstein, that area increased to about 3 000 ha in 2006 (MLUR 2006). Extensively used grassland managed by contractual conservation may not be converted to arable farm land, drainage may not be intensified, and the application of pesticides and fertilizers is prohibited. Pro-Eiderstedt has developed a concept to manage approximately 10 000 ha of agricultural land by contractual conservation, however, the plan calls for only limited enforcement of the specified rules.

Critics of contractual nature conservation state that it has proved to be not too effective in the past (Nehls 2002). Contracts with strict rules are hardly attractive to farmers and are therefore very often rejected, even though only one third of such contracts in Germany contain special obligations regarding environmental protection while the largest share of them contains only general rules for extensive land use.

Advocates of strict rules to protect the grassland areas propose to strengthen the extensive grassland use without increasing incentives of a more intensified management. The NABU calls for a special premium for the farmers who extensively manage their grassland (NABU 2004) to offset the economic disadvantages of grassland farming in comparison to crop production. An important aspect of this plan is to grant premiums for arable farm land and for grassland separately and with particular reference to the location. Additionally, the premiums must be revoked in case of a conversion of the land. However, the enforcement of such a premium system would be quite complicated and subject to a large number of exceptions.

In addition to economic stimulation, environmental interest groups endorse direct measures to protect ecologically valuable land. The European directive Natura 2000 requires the members of the EU to identify protected sites according to the European Conservation of Wild Birds Directive. The former environmental minister of Schleswig-Holstein, Klaus Müller of the Green Party, proposed to declare 24 648 ha of Eiderstedt, which is practically the whole area of the peninsula except for the settlements, as sanctuary. This caused fierce opposition as this plan exceeded the minimum requirements of the directive (SH-Landtag 2004). Farmers feared that the declaration of a large protected area would bring them economic disadvantages as new investments and expansions of agricultural activities would be severely regulated.

Instead, three separate bird sanctuaries on Eiderstedt have been declared: one around the town of Westerhever in the Northwestern corner of Eiderstedt and two others in central Eiderstedt near Poppenbüll and Kotzenbüll (Fig. 3). The goal of declaring these sanctuaries was to maintain these sites as habitats for migrating and breeding bird species (MLUR 2006) by preserving the many ponds and drainage drills by limiting the extent of agricultural use. Farmers criticize even this declaration arguing that the EU Conservation of Wild Birds Declaration is only valid for natural and not for cultivated land and does not apply to Eiderstedt as the whole landscape is anthropogenically cultivated in its entirety already for centuries.

Currently, no agreement between the different interest groups appears to be in reach. In case no additional sites are declared as sanctuaries in the future, the remainder of the agricultural land on Eiderstedt may be subject to conversion in the near future. This would alter the appearance of the landscape on Eiderstedt such that arable farm land would become the dominant form of land use for the first time in more than one and a half centuries.

4 Scenarios of land use development in the next decades

In order to be able to assess the possible ecological consequences of such land use change, different scenarios are developed. The scenarios are based on the assumption that the plan to drastically increase the amount of arable farm land on Eiderstedt to two thirds of the entire agricultural land area is actually realized within the next couple of decades. Due to the lack of information in the propositions on which areas are to be converted, three different patterns of land use change are compared in the following. The agricultural land use patterns in the course and after the completion of the planned conversion are identified for all scenarios. They differ quite substantially, depending on the development path applied.

The first scenario considers a pattern of land use change, in which land is primarily converted along the main roads through Eiderstedt and in only recently diked marshland (Fig. 4). Such a development is particularly likely if a lot of biofuels are to be grown on Eiderstedt in the future. Because these crops would need to be transported to the power plants from where they are grown, producing them as closely as possible to already existing infrastructure makes this task significantly easier.

If the land use change originates from the main roads through Eiderstedt, the landscape becomes very patchy during the conversion process. Halfway through the conversion process, uniform areas of grassland can only be found in the three declared bird sanctuaries and in their vicinity in central Eiderstedt (Fig. 4). The Eastern part of Eiderstedt consists of a mix of many small areas of both land uses. It has to be noted that in the early phase of the conversion process land closer to the coastal areas of Eiderstedt are more likely to be converted than the more central parts of the peninsula.

At the end of the conversion process, only some patches of grassland remain scattered throughout Eiderstedt (Fig. 4). These are generally quite fragmented, except for the areas around the three bird sanctuaries, in which larger uniform areas of grassland remain intact. These areas would have to serve as primary breeding grounds for the remaining meadowbirds. In all scenarios, the region around Westerhever only remains a uniform grassland area because it is a declared bird sanctuary. If it had not been declared a protected site, the Northwestern tip of Eiderstedt would also have been converted into arable farm land to a large extent.

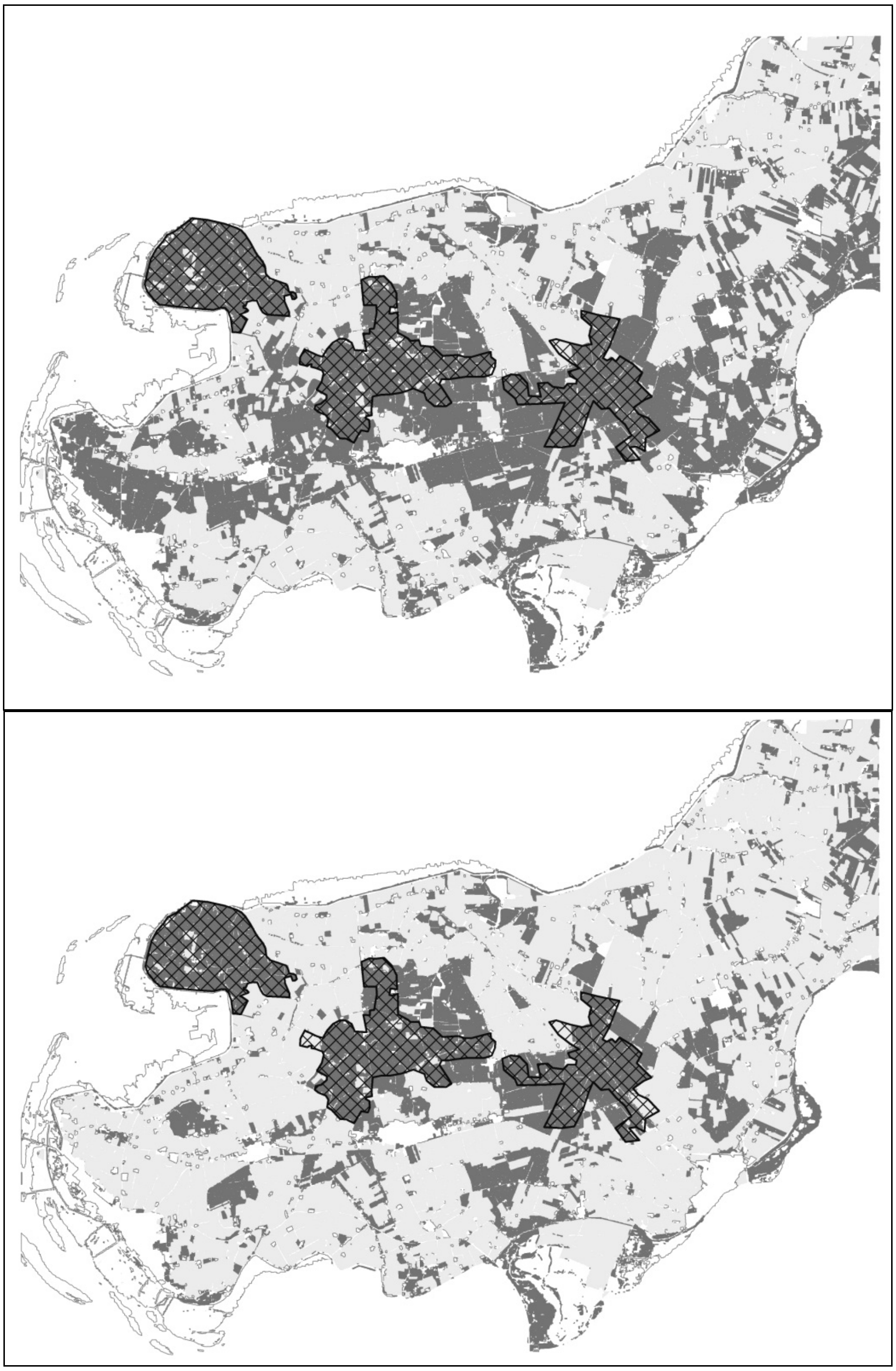

Figure 4: Agricultural land use on the Eiderstedt peninsula in 2015 (top panel) and 2025 (bottom panel), if land use change originates along the main roads across Eiderstedt

The second pattern is based on the assumption that it is best to grow crops on large continuous patches of land. Therefore, in this pattern land is primarily converted in areas around already existing arable farm land (Fig. 5). In this case the conversion process is more coherent and produces a less fragmented land use pattern.

During this conversion process, a large region of grassland remains in central Eiderstedt. It does not only encompass the two bird sanctuaries but also substantial areas in their vicinity (Fig. 5). The large size of this uniform grassland area increases its ecological value as breeding habitat for meadowbirds. Similar to the previous scenario, the arable farm land is mainly located in the regions close to the coast but it is combined into larger units so that crop production can be more efficient in this scenario than in the previous one.

Figure 5: Agricultural land use on the Eiderstedt peninsula in 2015 (top panel) and 2025 (bottom panel), if land use change extends outward from already existing patches of arable farm land

The distribution of the remaining grassland in 2025 in this scenario (Fig. 5) is similar to the one considered earlier, except for the region North of St. Peter-Ording, which remains grassland, and the area in central Eiderstedt, where less land is converted in the vicinity of the two bird sanctuaries. In contrast, patches converted to arable farm land are less fragmented, so that the degree of land use change appears to be even higher than in the previous scenario, even though this is not the case.

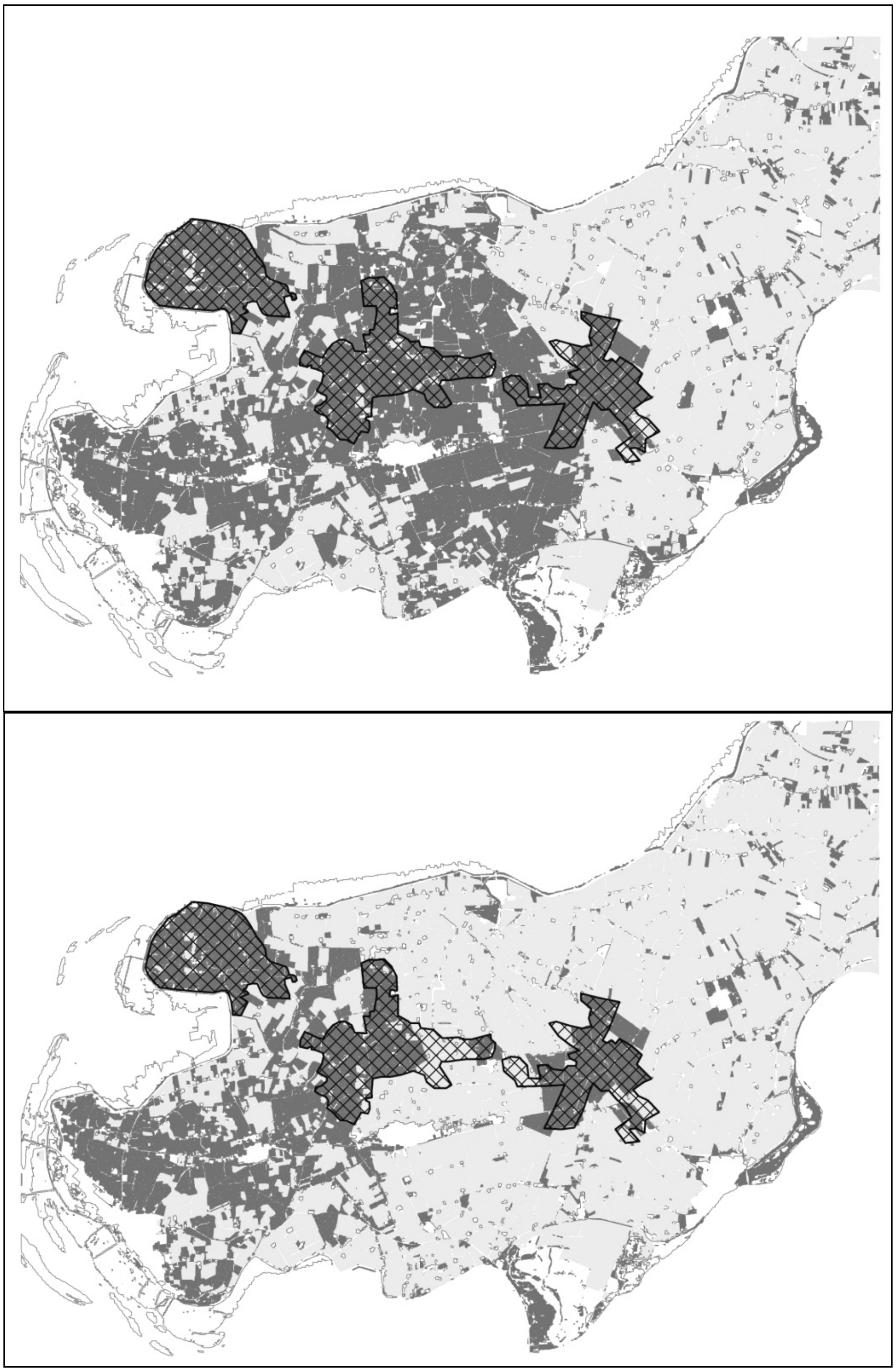

Figure 6: Agricultural land use on the Eiderstedt peninsula in 2015 (top panel) and 2025 (bottom panel), if land use change first occurs in the East and then progresses Westwards

The third pattern of conversion follows the premise that the less remote an area of land is, the more useful it is to be used for crop production. Since the Eiderstedt peninsula is connected to the rest of Schleswig-Holstein only in the East, this pattern of land use change converts grassland to arable farm land from East to West (Fig. 6).

By applying such a conversion pattern, it is ensured that the area of arable farm land used for crop production is more or less coherent, while the remaining grassland also consists of large patches as long as possible (Fig. 6). In the early phase of land use change, conversions are more likely to occur in the Southern part of Eiderstedt than in the North.

If two thirds of the agricultural land have been converted to arable farm land from East to West, practically all of the remaining grassland is confined to the area West of the town of Garding. Eastwards only bird sanctuary of Kotzenbüll remains more or less intact. However, there is even some land use change within the two bird sanctuaries in central Eiderstedt. This is likely to have an adverse influence on the overall ornithological habitat quality of these two special regions. Furthermore, large parts of the remaining grassland are in the vicinity of the towns of St. Peter-Ording and Tating, which are popular tourist destinations at the West coast of Schleswig-Holstein. This is likely to cause additional ecological difficulties due to increased stress imposed on the fauna caused by high anthropogenic frequentation.

5 Possible implications of a conversion of grassland to arable farm land

A large scale conversion of grassland to arable farm land throughout the Eiderstedt peninsula will not only change the appearance of the entire landscape but also have an impact on the number of breeding pairs of meadowbirds supported by the habitats. The scenarios described above are applied in a GIS assessment to determine the altered carrying capacity of the Eiderstedt peninsula for key bird species (Schleupner & Link 2007). The results indicate that the pattern of agricultural land use change has a profound influence on how the number of breeding pairs develops.

The three scenarios mainly differ in the location of the remaining grassland areas and in their degree of fragmentation. The fragmentation is highest if the conversion originates along the existing infrastructure on Eiderstedt, which worsens the quality of the grassland that is not converted to arable farm land. In contrast, the area of coherent regions of agricultural land use is largest if the conversion proceeds Westwards across Eiderstedt. However, since the remaining bird habitats in the bird sanctuary near Kotzenbüll become quite isolated and most of the other suitable breeding habitats are located in proximity to major tourist destinations, the bird density in those habitats is likely to decline over time, amplifying the pressure on the bird populations of Eiderstedt caused by the reduction in size of the suitable breeding habitats.

Overall, the quality of the Eiderstedt peninsula as breeding habitat for meadowbirds decreases substantially as a consequence of a large scale land use change. As the density of breeding pairs of four important species declines, the number of individuals supported by the habitats will be reduced at a disproportionately high rate (Schleupner & Link 2007). Even the declaration of the three bird sanctuaries on Eiderstedt will prove to be insufficient to counter this trend since the sanctuaries are also negatively influenced by changes in their vicinity whose influence carries over into the protected areas.

In addition to adverse ornithological impacts, a substantial land use change on Eiderstedt can have an influence on income generated by tourism. Eiderstedt is a famous destination due to its extensive grassland areas and the large numbers of breeding and migrating birds to be observed. The general appearance of Eiderstedt to visitors will change if large parts of grassland are replaced by arable farm land for crop production. How this would influence the tourist industry on the peninsula still needs to be determined separately. The controversy about land use development can only be solved if a compromise can be reached between the ecological demands of the ornithological fauna, the economic interests of farmers, and the aesthetic expectations of tourists visiting the Eiderstedt peninsula.

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References

Feddersen, F. (1853). Beschreibung der Landschaft Eiderstedt. Schlüter Verlag, Tönning/Altona, Germany, 301 p. (in German).

Fischer, L. (ed.) (1997). Kulturlandschaft Nordseemarschen. Nordfriisk Instituut, Bredstedt/Westerhever, Germany, 254 p. (in German).

Hammerich, H. (1984): Eiderstedts Landwirtschaft – gestern und heute. Husum Druck- und Verlagsgesellschaft, Husum, Germany, 71 p. (in German).

Hötker, H., H. Köster & K.M. Thomsen (2005): Wiesenvögel auf Eiderstedt und in der Eider-Treene-Sorge Niederung/Schleswig-Holstein im Jahre 2001. Corax 20, 1-17. (in German).

InfoNet Umwelt (2007). www.umwelt.schleswig-holstein.de (last visit: June 25, 2007).

Landesvermessungsamt Schleswig-Holstein (LVermA-SH) (2007a): Digitale Topographische Karte 1:25000 – Vorläufige Ausgabe (DTK25-V) of the Preußische Landesaufnahme 1878, pages 1518, 1519, 1617, 1618, 1619, 1717, 1718, and 1719.

Landesvermessungsamt Schleswig-Holstein (LVermA-SH) (2007b): Digitale Topographische Karte 1:25000 – Vorläufige Ausgabe (DTK25-V) of 2002, pages 1518, 1519, 1617, 1618, 1619, 1717, 1718, and 1719.

Landtag des Landes Schleswig-Holstein (SH-Landtag) (2004): Neuer Disput um FFH-Umsetzung. www.sh-landtag.de/plenum_online/april2004/texte/39_ffh.htm (last visit: June 28, 2007). (in German).

Meier, D. (2001): Landschaftsentwicklung und Siedlungsgeschichte des Eiderstedter und Dithmarscher Küstengebietes als Teilregion des Nordseeküstenraumes, Teil 1 und 2. Habelt Verlag, Bonn, Germany, 287 & 175 p. (in German).

Ministerium für Landwirtschaft, Umwelt und ländliche Räume Schleswig-Holstein (MLUR) (2006): Bekanntmachung des Ministeriums für Landwirtschaft, Umwelt und ländliche Räume vom 7. Februar 2006. Auswahl Europäischer Vogelschutzgebiete. Beteiligung der Betroffenen nach § 20 c Abs. 2 Landesnaturschutzgesetz. www.natura2000-sh.de (last visit: June 25, 2007). (in German).

Naturschutzbund Deutschland (NABU) (2004): Eiderstedts Grünland muss erhalten bleiben! Resolution NABU Landesvertreterversammlung 25. April 2004. schleswig-holstein.nabu.de/modules/presseservice_schleswig_holstein/index.php, (last visit: June 28, 2007). (in German).

Naturschutzbund Deutschland (NABU) (2005): Akteneinsicht: Der Fall „Eiderstedt". schleswig.holstein.nabu.de/m05/m05_04/04750.html (last visit: June 27, 2007). (in German).

Nehls, G. (2002): Grünlandnutzung und Naturschutz – die Flächenprämie bringt's zusammen. In: Agrarbündnis e.V. (ed.): Der kritische Agrarbericht. ABL Bauernblatt Verlags-GmbH, Hamm, Germany, pp. 228-233 (in German).

Schleupner, C. & P.M. Link (2007): Potential impacts on important bird habitats in Eiderstedt (Schleswig-Holstein) caused by agricultural land use changes. Hamburg University, Research Unit Sustainability and Global Change, Working Paper FNU-138, 22 p.

Statistisches Amt für Hamburg und Schleswig-Holstein (Stat A Nord) (1950-2004): Statistische Berichte zur Landwirtschaft in Schleswig-Holstein auf Gemeindeebene, multiple volumes. Kiel, Germany. (in German).

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Potential synergies between existing multilateral environmental agreements in the implementation of Land Use, Land Use Change and Forestry activities

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Abstract

There is potential for synergy between the global environmental conventions on climate change, biodiversity and desertification: changes in land management and land use undertaken to reduce net greenhouse gas emissions can simultaneously deliver positive outcomes for conservation of biodiversity, and mitigation of desertification and land degradation. However, while there can be complementarities between the three environmental goals, there are often tradeoffs. Thus, the challenge lies in developing land use policies that promote optimal environmental outcomes, and in implementing these locally to promote sustainable development. The paper considers synergies and tradeoffs in implementing land use measures to address the objectives of the three global environmental conventions, both from an environmental and economic perspective. The intention is to provide environmental scientists and policy makers with a broad overview of these considerations, and the benefits of addressing the conventions simultaneously.

Keywords*:* Climate change, LULUCF, Biodiversity, Desertification, Sustainable development.

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1 Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) recognizes that management of the terrestrial biosphere can contribute to mitigation of climate change. Within the context of climate change policy, emissions and removals of greenhouse gases resulting from direct human-induced impacts on the terrestrial biosphere are accounted within the sector known as land use, land use change and forestry (LULUCF)[1]. Besides their relevance to the UNFCCC objectives, measures undertaken in the LULUCF sector are relevant to several other multilateral environmental agreements that have entered into force during recent years, particularly the United Nations Convention to Combat Desertification (UNCCD, United Nations, 1994) and the Convention on Biological Diversity (CBD, United Nations, 1992).

This paper focuses on the implications of LULUCF measures[2] in relation to the objectives of the UNCCD, CBD and the UNFCCC. The potential synergies and possible trade-offs between the objectives of measures that may be promoted under the three

[1] National GHG inventories are currently prepared following the Revised 1996 IPCC Guidelines for national Greenhouse Gas Inventories and Common Reporting Formats, in which the Land Use Change and Forestry (LUCF) sector is reported separately from the Agriculture, Energy, Industrial Processes and Waste sectors (Houghton et al. 1997). The 2006 Guidelines combine reporting for the Agriculture and LUCF sectors under the title Agriculture, Forestry and Other Land Use (AFOLU) (IPCC 2006). In Kyoto Protocol accounting, carbon stock changes and non-CO2 emissions from afforestation, reforestation and deforestation, and, if elected, forest management, cropland management, grazing land management and revegetation are reported under "Land use, land use change and forestry" (LULUCF), except for non-CO_2 agricultural emissions, which are reported under Agriculture, and fuel use in agricultural and forestry operations which are reported in the Energy sector. The term "land use" is here used to include all emissions and removals associated with agricultural and forestry land uses.

[2] LULUCF measures are here defined as changes in land use and land management undertaken to reduce GHG emissions. Specific measures are discussed in Section 4 and Table 2.

environmental conventions are discussed, both from an environmental and economic perspective, and policy options for facilitating beneficial land management and land use changes are briefly outlined. The paper reflects the views and experience of the authors, and is intended to provide environmental scientists and policy makers, who commonly focus on one specific field, with a broad overview of these considerations, and the benefits of addressing the conventions simultaneously.

2 Historical background

Human activity inevitably has impacts on the land. As expressed in the Stockholm Declaration (United Nations Conference on the Human Environment, 1972) "Man is both creature and moulder of his environment". The first major human-induced land use changes are associated with the burning practices of indigenous peoples, for example in Australia (Yibarbuk et al., 2001) beginning in the late Pleistocene and North America in the early Holocene (MacCleery, 1999): altered fire regimes, whereby aboriginal mosaic burning replaced infrequent intense lightning-induced fires, are considered responsible for displacement of forests by woodlands and grasslands, and thus a reduction in carbon stocks. Subsequently, the first agricultural revolution of the Neolithic (Mazoyer and Roudart, 1997) with extensive deforestation phenomena due to "slash and burn" technologies that dominated for thousands of years, substantially affected land use patterns in many parts of the world. The relationships between Neolithic land use, world-wide migration patterns, and technological evolution have been explored by Diamond (1999), and described mathematically by Wirtz and Lemmen (2003). Could it be that land use contributed to the change in climate during the mid-Holocene shift? Recent definitions of the Anthropocene place the start of the Anthropocene in the late eighteenth century (Crutzen, 2002), when analyses of air trapped in polar ice show the beginning of growing global concentrations of carbon dioxide and methane. Certainly Neolithic agriculture had a negligible impact on climate, but influence on early land degradation phenomena, like erosion and decline of organic matter content in soils, is apparent: most of the land degradation phenomena in the Mediterranean basin commenced in the Neolithic, subsequently reaching a peak during Roman times (Lowdermilk, 1953); extensive erosion by water in the Apennines of Central Italy that can be considered as early forms of desertification in the area. Soil salinisation caused by poor irrigation practices led to widespread land degradation in Mesopotamia in 2000 BC (Jacobsen and Adams, 1958).

From the perspective of global climate change, greenhouse gas emissions from human influence on the biosphere started well before the inception of the Anthropocene, as defined by Crutzen. Figure 1 represents in a simplified way the changes in the terrestrial organic carbon pool generated from the sequence of aboriginal burning, through agricultural revolutions, till today, and depicts the projected changes if positive LULUCF measures are implemented in the future. This historical time trend demonstrates that human activities have generally tended to reduce the terrestrial carbon pool over time. It also exemplifies the concept that the potential to restore the carbon pool is limited by resource constraints[3].

Insert Figure 1 near here

[3] The natural resource constraints at a site determine the natural carbon carrying capacity, however, human intervention can overcome natural resource constraints, and thereby raise the maximum potential carbon stock at a site.

The natural capacity of an environment should be a guide to the selection of appropriate LULUCF measures for a particular site. Paleovegetation maps, showing the distribution of the major vegetation types before the Anthropocene, give an indication of the natural carbon carrying capacity of different regions, based on local biophysical constraints (Crowley, 1995; Adams and Faure, 1997). The notion that LULUCF measures are site specific is of crucial importance and will be addressed in more detail in subsequent sections of this paper.

3 Policy instruments steering sustainable land management

Land use and land use change are driven by economic and social influences, but with the recognition of the concept of sustainable development, environmental and sustainability concerns have started to influence land use policy. The report of the World Commission on Environment and Development (WCED), *Our Common Future* (WCED, 1987), also known as the "Brundtland Commission Report", has significantly influenced sustainability policy in the western world (eg MacNeill, 1989, p11). The WCED report promoted sustainable development as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. Out of this framework the term "sustainable land management" was defined.

Numerous multilateral environmental agreements have been ratified in recent years addressing specific aspects of sustainable land management, environmental degradation and resource depletion; those that influence, or are influenced by, LULUCF actions are listed in Table 1. Three conventions emanating from Agenda 21 (United Nations, 1992c)., established at the UN Conference on Environment and Development (UNCED) in Rio de Janeiro in 1992, have particular relevance to LULUCF:

- Framework Convention on Climate Change (UNFCCC)
- Convention on Biological Diversity (CBD)
- Convention to Combat Desertification (UNCCD)

Insert Table 1 near here

3.1 LULUCF within UNFCCC

The ultimate objective of the UNFCCC, adopted in 1992, is to stabilize greenhouse gas emissions "at a level that would prevent dangerous anthropogenic (human induced) interference with the climate system". Parties agreed to develop and implement policies and programs to reduce greenhouse gas emissions, to report annual inventories of emissions, and to provide support to developing countries. The commitments of parties were strengthened through the adoption, in 1997, of the Kyoto Protocol, under which industrialised countries committed to individual legally-binding targets.

Recognising the contribution of the terrestrial biosphere to emissions and removals of greenhouse gases, net change in carbon stocks in biomass, litter and soil are included in inventory reporting. The basic premise is that through LULUCF measures the terrestrial carbon pool can be increased, by increasing the above and below ground biomass and consequently the soil organic matter pool. Thus, the Kyoto Protocol allows parties to offset emissions from other sectors against removals generated through specific LULUCF activities: under Article 3.3 of the Protocol, removals due to afforestation and reforestation since 1990 are accounted towards commitments. Emissions resulting from deforestation must also be included. Under Article 3.4 parties can elect to include additional LULUCF activities, viz. forest management, cropland management, grazing land management and revegetation.

Article 12 of the Kyoto Protocol defines a Clean Development Mechanism whereby developed countries (the “Annex 1” countries that have an emissions target under the Protocol) earn “certified emissions reductions” through projects implemented in developing countries. This mechanism is intended to promote projects that contribute to sustainable development in the host country. Afforestation and reforestation projects are eligible, though other LULUCF measures are not. In order to demonstrate contribution towards the goals of sustainable development, project proponents are required to assess the environmental and socio-economic impacts of the proposed project, and to seek input from local stakeholders.

3.2 LULUCF within CBD

The goals of the Convention on Biological Diversity (CBD) are “the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources” (CBD, 1992). The provisions in the convention require parties to, inter alia, implement measures to protect biodiversity, and particularly to protect and promote recovery of threatened species. Measures include establishment of a system of protected areas, and promotion of “environmentally sound and sustainable development” adjacent to protected areas. The provisions of the CBD are general in nature, and do not involve binding targets. They include financial contribution towards biodiversity protection in developing countries, scientific and technical co-operation between parties, access to genetic resources, and the transfer of environmentally-sound technologies.

In 2002, recognising that the rate of loss of biodiversity was continuing to increase, the parties to the convention agreed to a strategic plan intended to halt the loss of biodiversity. Parties committed to the “2010 Biodiversity target”, that is “to achieve by 2010 a significant reduction of the current rate of biodiversity loss at the global, regional and national level as a contribution to poverty alleviation and to the benefit of all life on earth”. Outcome-oriented targets, on a global basis, have been agreed, and include a target of “at least 30 per cent of production lands managed consistent with the conservation of plant diversity”. Actions to be taken include conserving production species, protecting other species in the landscape, and introducing management practices that minimise adverse impacts on surrounding ecosystems, such as by reducing export of agri-chemicals and preventing soil erosion.

The strategic plan includes the goal to reduce pressures from habitat loss, land use change and degradation, and unsustainable water use, and to enhance resilience to climate change. Parties are to implement national polices and programs targeted toward these goals.

3.3 LULUCF within UNCCD

The United Nations Convention To Combat Desertification (UNCCD, 1994), the third of the Rio Conventions, is often called the “convention of the poor”. Its main focus has been to combat desertification and mitigate the effects of drought in developing countries, particularly sub-Saharan Africa. Desertification, defined as land degradation in dryland areas, is as much a social and economic issue as an environmental concern. Therefore, as its main target the UNCCD aims to fight poverty and promote sustainable development and is consequently mostly oriented towards development aid measures rather than environmental protection.

Land degradation is estimated to affect 10 to 20% of the world's drylands (Millennium Ecosystem Assessment, 2005a). Desertification is caused by climate variability and unsustainable human activities, such as overcultivation, overgrazing, deforestation, and poor irrigation practices. These practices lead to erosion of topsoil, loss of soil organic matter, and soil salinisation, which in turn cause loss of biological and economic productivity and diversity in croplands, pastures, and woodlands. Deforestation in dryland regions of Australia, North America, South Africa, Iran, Afghanistan, Thailand and India has led to development of dryland salinity. Under the convention, parties agreed to implement national, sub-regional, and regional action programmes, and to seek to address causes of land degradation, such as international trade patterns and unsustainable land management.

3.4 Synergies between the conventions

Each of the three global environmental conventions deals with the interrelationships between humans, animals, plants, soil, air and water. The environmental issues are themselves intertwined: climate change is a major threat to conservation of biodiversity and is likely to exacerbate desertification and drought in some regions; deforestation reduces biodiversity, reduces carbon stocks in biomass and soil thereby exacerbating climate change, and can lead to desertification; desertification further contributes to climate change through increase in land-surface albedo; dryland salinity, a symptom of desertification, threatens biodiversity. An in-depth analysis of the negative feedback loops linking desertification, climate change and biodiversity loss has been recently published (Gisladottir and Stocking, 2005). The relationships between desertification and LULUCF have been extensively reviewed in the Millennium Ecosystem Assessment (2005b).

The impacts on biodiversity and land degradation of LULUCF measures undertaken for mitigation of climate change are further explored in Section 4. There are many opportunities to build synergy among the activities undertaken in support of these various commitments. These linkages mean that it is vital for the measures implemented under these conventions to be integrated. There are multiple benefits from seeking synergy in implementation of the conventions: strengthening the effectiveness of actions undertaken in support of the conventions and ensuring efficient use of human and financial resources in planning, implementing, monitoring and reporting. The need for monitoring, prediction, mitigation and adaptation are common to all three conventions; besides efficiencies from linking these activities, such as through sharing data and tools, development of policy mechanisms and approaches will benefit from sharing collective wisdom on successful approaches. The economic benefits of joint regulation are further explored in Section 5.

The CBD’s ad hoc technical expert group on Biological Diversity and Climate Change identified opportunities for mitigating climate change, and for adapting to climate change, while enhancing the conservation of biodiversity (CBD, 2003).

The United Nations Forum on Forests’ Collaborative Partnership on Forests (CPF) program aims to foster cooperation and coordination among international organizations that promote Sustainable Forest Management. Activities of the CPF include work on harmonising terms and definitions used in forest management, and facilitation of streamlining of reporting on forest issues to the UNFCCC, CBD and UNCCD. (UNFF, undated)

The parties to the conventions have acknowledged the convergence of objectives of the three Rio conventions, accepted the necessity to integrate actions to ensure optimal environmental outcomes, recognised the benefits of exploiting the synergies, and therefore called for enhanced collaboration among the conventions (UNFCCC, 2004).

Efforts to integrate the conventions are led at the international level by the Joint Liaison Group (JLG) of the UNFCCC, CBD and UNCCD, established in 2001. The JLG facilitates collaboration between the secretariats of the three Conventions and promotes integration through sharing of information, coordination of activities, and identification of measures that simultaneously address all three issues (CBD, undated; UNFCCC, 2004). Actions include a workshop on synergies between the three conventions with respect to forests and forest ecosystems (UNCCD, 2004). At its fifth meeting (FCCC/SBSTA/2004/INF.9), the JLG discussed the potential for the Global Environmental Facility (GEF), which provides support for capacity building and technology transfer, to support synergies by promoting implementation of projects in a coordinated and cooperative manner.

By definition, the UNCCD applies only in dryland regions, that is, the arid, semi-arid and dry sub-humid. Thus, integration of the three conventions is not universally applicable. However, issues of land degradation occur globally. Just as it is desirable to seek synergy in implementation of the UNFCCC, CBD and UNCCD in dryland regions, it is appropriate to look for mutually beneficial actions that meet the objectives of climate change mitigation, biodiversity protection and protection against relevant forms of land degradation in those regions not covered by the UNCCD.

4 LULUCF activities and their influence on climate change, biodiversity and desertification

LULUCF measures implemented to mitigate greenhouse gas emissions may also affect, positively or negatively, desertification and conservation of biodiversity. The influences of broad categories of LULUCF actions are discussed below, and impacts of specific actions are listed in Table 2. Before considering these impacts, we will firstly outline the measures by which impacts on each of the three environmental attributes are quantified.

INSERT TABLE 2 NEAR HERE

4.1 Quantifying impacts of LULUCF measures

4.1.1 Climate change impacts

The carbon sequestration impact of change in land use or land management on an area of land is determined from the difference in average carbon stock between the new system and the previous land use. Quantifying impacts of LULUCF measures requires estimation of biomass growth and change in soil carbon, using measurements (eg MacDicken, 1997; Janik et al., 1998; Brown et al., 2006), empirical or process based models (eg Masera, 2003; Richards and Evans, 2004; Kurz and Apps, 2006), or look-up tables (such as “Tier 1” methods for reporting national greenhouse gas inventories (IPCC, 2006)). In addition to emissions and removals estimated from C stock change, emissions of non-CO_2 GHGs (particularly N_2O and CH_4) should be included in assessing climate change impact.

Internationally agreed methodology for estimating emissions and removals from LULUCF activities is given in publications of the IPCC (Houghton, 1997; Penman, 2003, IPCC, 2006).

Forest biomass can be used for bioenergy or for products that can substitute for more greenhouse-intensive products, displacing fossil fuel emissions. The mitigation benefits of these downstream activities should be included in the assessment of the impact of LULUCF activities.

4.1.2 Biodiversity impacts

While greenhouse gas mitigation potential is readily estimated by internationally agreed methodologies, estimating biodiversity value is very much more challenging. Predicting impacts of change in land use or land management often involves a degree of subjectivity and reliance on surrogates, and may include measures of taxonomic diversity, conservation status, patch size and shape, and connectedness. Many indices for quantifying and predicting biodiversity value of proposed land use changes have been developed (eg Freudenberger and Harvey 2003; Oliver and Parkes, 2003; Gibbons et al., 2005).

4.1.3 Desertification impacts

Like biodiversity, the impact of land use and land use change on desertification is difficult to quantify. Major causes of desertification are deforestation, overgrazing, cultivation of unsuitable sites, and poor irrigation practices, that lead to wind and water erosion, dryland and irrigation-induced salinity. Because the symptoms of desertification are diverse, quantifying potential benefits is challenging. Measures include stream turbidity and salinity, sediment and salt loads in waterways, water table depth, incidence of dust storms. Predicting impacts of LULUCF activities on these attributes requires complex spatial process-based modelling utilising data on local soil type, geology, elevation, and climate. Assessment of land use practice with respect to land capability can provide an indicator of risk of land degradation (Emery, 1985).

4.1.4 Integrated measures

Integrated measures seek to evaluate the combined impact of land use activities on the target environmental objectives. However, these measures are difficult to establish because environmental qualities are estimated in different physical units. Frequently proposed remedies involve the computation of environmental indexes or money equivalents for environmental goods. Environmental benefits indices are calculated from normalised measures of each biophysical attribute, weighted and aggregated to give a single score that integrates all environmental attributes of interest (eg index applied in the Conservation Reserves Program in the USA (USDA, 1999, 2003)). Arnalds' (2005) Sustainability Index Model considers social impacts in addition to assessing the impact of the proposed land use on land condition, including long term impact on the resource base. Measures of "inclusive wealth" (Arrow et al., 2003) value natural and human capital, as a metric for assessment of sustainability.

4.2 Afforestation and reforestation

The impact of afforestation/reforestation on net GHG emissions, biodiversity and desertification is dependent on the features of the forest system established and the land use that it replaces.

The maximum potential carbon stock at a site, that is, its carbon carrying capacity (Gupta and Rao, 1994), is determined by climatic and edaphic factors that determine the net ecosystem productivity, and the influence of disturbances, such as fire, that together determine the net biome productivity[4]. The carbon stock of a managed forest is a function of site productivity and silvicultural management (stocking rate, species, pruning, thinning). The carbon sequestration benefit of a change in land use or management is determined by the increase in carbon stock of biomass and soil between the original and new land uses. Practices that maximise carbon sequestration in forest biomass are those that enhance forest growth: matching species to site, good site preparation, managing weed competition, and applying fertiliser to correct nutrient deficiencies and maintain fertility. Usually, practices that enhance forest growth will also build soil carbon stocks, through increased organic matter addition. However, where soil carbon stocks are high, and mineralisation is limited by nutrient deficiency, fertilisation can cause loss of soil carbon (Cleveland and Townsend, 2006). In forest systems managed for sawlog production, there will be a trade-off between management that maximises forest carbon stocks and returns from wood products, because silviculture to maximise value of stems (i.e. thinning and pruning) will reduce the total stand biomass and thus stock of carbon. Short rotation plantations managed for fibre production will have a lower average carbon stock, across successive rotations, than long rotation plantations managed for timber production.

Afforestation/reforestation of cropped or degraded land will enhance soil carbon stocks as well as biomass stocks. However, reforestation of pasture land may lead to a loss of

[4] Climate change will alter the carbon carrying of a site.

soil carbon, at least in the short term (Paul et al, 2002; Cowie et al, 2006). Reforestation with coniferous species generally decreases soil carbon stocks by around 15% (Guo and Gifford, 2002; Paul et al., 2002), partly offsetting the mitigation benefits of sequestration in tree biomass.

The mitigation benefit through reforestation of a particular site is finite – determined by the difference in long term average carbon stock between the forest system and prior land use. However, the net mitigation benefit of afforestation or reforestation projects can be increased through utilisation of forest biomass for bioenergy, thereby providing ongoing mitigation through avoidance of fossil fuel emissions (Marland and Schlamadinger, 1997). Afforestation and reforestation projects can provide an additional benefit through provision of building materials that can displace more greenhouse-intensive materials (eg Börjesson and Gustavsson, 2000; Pingoud et al., 2003).

Reforestation of cropped or degraded land can have positive impacts for biodiversity conservation and mitigation of degradation. Afforestation and reforestation with native species may help promote the return, survival, and expansion of native plant and animal populations. If the plantation provides a corridor function for species migration (for instance under climate change pressure) and gene exchange, biodiversity will be positively affected.

When sited strategically within the catchment to reduce salt export and manage deep drainage, reforestation can mitigate dryland salinity, protecting productivity of agricultural land (eg Stirzaker et al., 2002; Ellis et al., 2006) and the biodiversity in conservation areas threatened by rising saline water tables (Goudkamp et al., 2003).

Plantations may benefit biodiversity indirectly if they reduce pressures on natural forests by serving as sources for forest products.

Systems designed to maximise carbon sequestration may not deliver optimal outcomes for other environmental objectives. Biodiversity value is likely to be lowest in short rotation monocultures, greater in long rotation sawlog plantations, and highest in permanent mixed stand of endemic species, though growth rate, and therefore carbon sequestration, is likely to be greater in an exotic monoculture plantation, at least in the short term. Afforestation and reforestation activities that replace species-rich grasslands or shrublands, while delivering climate change benefits, are likely to reduce biodiversity.

4.3 Agroforestry

Agroforestry refers to the integration of trees (alleys, tree belts, small block plantings, riparian strips) into cropping or pastoral systems. Increase in use of trees in agricultural landscapes through agroforestry systems has a large potential to sequester carbon, both in woody biomass and in soil (Vagen et al., 2005), due to the vast areas of land used for agricultural purposes (Montagnini and Nair, 2004). Integration of a tree component may also enhance carbon stock of the adjacent agricultural enterprises such as by reducing wind erosion and providing habitat for beneficial organisms.

Agroforestry can be beneficial for biodiversity, especially in agricultural regions dominated by crop monocultures. As with afforestation and reforestation, agroforestry is most beneficial for biodiversity when it replaces degraded or deforested sites. Even small tree blocks or individual paddock trees can provide valuable contributions to biodiversity in agricultural landscapes (Kavanagh et al., 2005).

Agroforestry is recognised as a major contributor to combating desertification, particularly through reduction in soil erosion (FAO, 1992), and agroforestry programs are major components of the national and regional action programmes under the UNCCD.

Agroforestry can be effective in managing dryland salinity: strategically sited belts of trees within an agricultural landscape can intercept runoff and lateral flow, reducing salt movement to streams and accession to groundwater (Ellis et al., 2006). Tree belts can lower the water table locally, permitting cropping on sites that have become unproductive due to shallow saline groundwater (Robinson et al., 2006).

Agroforestry increases the diversity of agricultural systems, enhancing resilience, both ecologically and economically. Agroforestry may be more acceptable to communities than large scale reforestation, as traditional agricultural commodities can continue to be produced, and agroforestry can be introduced through modification of existing farming practices rather than complete change in land use.

4.4 Revegetation

Revegetation refers to enhancement of carbon stocks other than by establishment of vegetation that meets the definition of “forest”. This may include establishment of shrubs, or tree planting at low stocking rate. Revegetation practices have limited scope to increase carbon sequestration compared with reforestation, but may have a significant impact through increase in soil carbon stocks. Revegetation can have major benefits for biodiversity and land degradation.

4.5 Land management

The term land management refers to the management of forests, croplands and grazing lands.

Forest management practices that mitigate GHG emissions are those that increase forest carbon stocks, including reduction in disturbances such as fire, extending rotation length, and fertilisation. Management of fire to reduce widespread stand-replacing wildfires, and extending rotation length, also have positive impacts for conservation of biodiversity and mitigation of desertification.

In cropping and grazing systems, the major factors that can deliver net greenhouse gas emissions reduction are increase in soil C stocks, and reduction in non-CO_2 emissions such as nitrous oxide from fertiliser application. Soil carbon stock reflects the balance between inputs, from plant litter or organic amendments, and losses due to oxidation and, to a lesser extent, erosion of topsoil (Cowie et al., 2006). Therefore, soil C stock is increased by practices that increase plant production (eg irrigation, fertilisation) and reduce loss of organic matter (eg reduction in tillage or grazing pressure) (Sampson et al., 2000). Due to the vast areas of cropping and grazing land, small increases per unit area can deliver significant mitigation of GHG emissions.

There is growing interest in the use of crops for production of biofuels and other non-food commodities. Use of ethanol or butanol produced by fermentation from sugar and starch crops, and biodiesel from oilseeds, can give significant mitigation benefit through substitution for fossil transport fuels (eg Sheehan et al., 1998; Farrell et al., 2006). Similarly, short rotation woody crops can be used to generate heat and electricity. Novel crops such as jatropha, crambe and guayule may play a role in replacing petrochemicals. Besides concern over climate change, recent sharp increases in fuel prices and concerns over energy security are added incentives for expansion of non-food crops. There is a risk that increased removal of biomass in bioenergy systems could reduce soil carbon, but as long as the root and leaf litter biomass, that constitute the major input to soil C, are retained on site, the impact on soil C of removal of biomass for bioenergy should generally be small (Cowie et al., 2006).

Modification of cropping and grazing practices impacts biodiversity. Generally, low intensity of fertilization, pesticide, and cutting and grazing promote a diverse and ecologically more desirable species composition (Muller, 2002; Buckingham et al., 2006). Practices that enhance soil carbon stock and prevent land degradation, will generally enhance conservation of native species present in those landscapes (eg Adl et al., 2006). However, pressure to expand crop production for biofuels may lead to conversion of pasture and woodland to cropland, with negative consequences for biodiversity.

Modification of cropping and grazing practices can have significant impacts in mitigation of desertification: reduced tillage and stubble retention, establishing perennial pastures, managing grazing to maintain vegetative cover will reduce land degradation through soil erosion; maintaining vegetative cover and introducing deep-rooted perennials can contribute to mitigation of dryland salinity. Risk of desertification is minimised when land is used according to its “capability”, that is, its ability to produce outputs without resulting in land degradation or negative off-site impacts. Land capability assessment determines the suitability for alternative land uses, within constraints imposed by hazards such as erosion, acidification and salinisation due to attributes including soil type, slope and landscape position. For example, an assessment of land capability would steer cropping away from steep slopes with erodible soil types toward lower slopes and soils with high aggregate stability. Pressure to expand cropping for production of biofuels may exacerbate land degradation, if lands of lower capability are cropped.

4.6 Avoidance of deforestation

Deforestation leads to immediate loss of biomass carbon stocks and associated soil carbon, and ecosystem services provided by forests. Clearing of natural forests directly reduces abundance of native species, and forest fragmentation may threaten survival of remnants. Fragmentation increases exposure to pest incursion and fire, may reduce populations below viable threshold, and reduces capacity to adapt. Many of the tropical forests in developing countries of South America and Asia have high carbon stocks, are recognised as biodiversity 'hotspots', and are threatened by deforestation (Huston, 1993). Deforestation leads to land degradation through soil erosion and development of soil salinity.

4.7 Common themes: beneficial practices

The impacts of LULUCF on climate change mitigation, protection of biodiversity, and desertification discussed above and listed in Table 2 are a result of the influence of human intervention on the underlying processes that drive greenhouse gas emissions, integrity of natural ecosystems, and land degradation, respectively. Climate mitigation benefits are afforded by practices that

- avoid deforestation, devegetation and degradation
- increase carbon stock in biomass pools
- reduce direct and indirect fossil fuel use (eg reduced tillage)
- protect and enhance the soil organic matter pool

- reduce emissions of non-CO_2 greenhouse gases.

Biodiversity is generally conserved by (inter alia)

- management of threats to natural ecosystems such as deforestation, dryland salinity
- increased diversity of production species in managed systems
- afforestation/reforestation and revegetation of arable and degraded land
- reduced soil disturbance and enhanced soil organic matter.

Protection against desertification is provided by

- maintenance of perennial vegetative cover to reduce erosion of topsoil
- maintenance of soil organic matter, which enhances aggregation, thus increasing infiltration and thereby reducing runoff and consequent erosion, and increases nutrient and water holding capacity, thus increasing productivity and resilience against drought.
- reforestation to mitigate dryland salinity
- management of irrigation practices and reforestation to reduce salinisation.

While some LULUCF measures can be detrimental to conservation of biodiversity or mitigation of land degradation, as indicated in Table 2, there are many opportunities for synergistic interactions. For example, many dryland ecosystems are sites of significant biodiversity; conservation and restoration of this habitat, while protecting these ecosystems, also increases carbon stocks, and reduces land degradation. Reversing land degradation builds resilience in natural and managed systems, sustaining production and protecting biodiversity. Activities that promote adaptation to climate change can also contribute to the conservation and sustainable use of biodiversity and sustainable land management. Measures that protect or enhance biomass and soil OM stocks tend to deliver benefits for all three environmental objectives. The most significant measures are reforestation, avoided deforestation and avoided degradation. The optimal mix of LULUCF measures will vary between locations because of the diversity in current land use, conservation status and socio-economic situation. Reducing deforestation is a major opportunity in countries such as Brazil, Indonesia, Malaysia (e.g., Fearnside, 2001). In countries such as India, China and the USA there are opportunities for reforestation of marginal and degraded agricultural lands, and modification of agricultural practices. Adjusting forest management regimes, and utilisation of forest products, are significant options in many industrialised countries.

5 Economic impacts of multi-environmental objectives in agriculture and forestry systems

Pursuing multiple environmental objectives through LULUCF measures will affect social welfare in various ways. Direct and indirect benefits of improved environmental quality must be weighed against economic surplus changes in commodity markets, diverse externality impacts, and policy transaction costs. Here we will focus on those impacts which differ between independent and joint regulation of climate change, biodiversity, and land degradation. In examining the economic implications, we will discuss the opportunity costs of LULUCF measures resulting from the scarcity of land, land use responses to environmental policy instruments, and externality feedbacks.

5.1 Land opportunity cost impacts

Numerous LULUCF measures have been classified as potentially beneficial with respect to one or more environmental qualities. While the direct costs of using these strategies may be quite low[5], the true cost of implementation may be much higher. An often ignored or underestimated[6] economic barrier for LULUCF measures relates to the scarcity of land and resulting rents. Economically, land rents constitute opportunity costs and equal the difference between marginal revenues[7] and marginal production cost for the most profitable land use option. This difference equilibrates market demand and supply of land based products and services, where scarcity limits supply. Thus, diverting land from productive agricultural zones for afforestation, perennial bioenergy crop plantations, conservation reserves, or soil protecting buffer zones causes a loss of agricultural profits and constitutes an indirect cost for these abatement strategies (Schneider and McCarl, 2006).

Four issues are important when considering LULUCF opportunity costs in the context of multi-environmental objectives. First, each internalized environmental objective changes the opportunity costs. For example, demand for carbon sequestration credits establishes a potential revenue opportunity for some LULUCF measures, equalling the product of sequestered carbon credits times the credit value. This increases the opportunity costs of all land use options with zero or negative sequestration rates. Furthermore, environmental subsidies frequently increase commodity prices because

[5] For example, to protect native ecosystems, direct costs may only consist of monitoring and enforcement.
[6] This refers to the omission of opportunity costs in a large number of abatement studies.
[7] Revenues also include subsidies where they apply.

abatement strategies decrease commodity supply. Higher commodity prices in turn increase possible revenues from land use and make land more valuable.

Second, opportunity costs differ considerably across regions and reflect site specific soil, climate, and market conditions. Particularly, the market profit is dependent on local commodity prices, crop yields, and production costs; the carbon sequestration benefit is determined by plant growth rate, which is dependent, inter alia, on climatic and edaphic regime; the biodiversity benefit is affected, inter alia, by the bioregion, current land use and distance to remnant native vegetation; the salinity mitigation benefit is governed by geology (whether there are salts in the soil and underlying rock strata), surface and groundwater hydrology (whether the site is discharging saline water to streams or groundwater) and plant growth rate (which determines water use); the soil retention benefit is dependent on soil type, slope, landscape position and location within the catchment.

Third, while opportunity costs are site specific, they also respond to macro-economic market adjustments. As trade barriers decline, price changes are transmitted globally. If large-scale environmental regulations reduce commodity supply, world prices and hence opportunity costs of these commodities will increase globally. Fourth, opportunity costs change in a nonlinear fashion. This applies especially to opportunity costs from food production. Demand for food is relatively inelastic because – regardless of food prices – people must eat a certain minimum amount but will not consume food beyond a certain level[8]. Supply shifts in inelastic commodity markets cause strong price

[8] We recognise that many people suffer from malnutrition and that low prices may cause a change of eating habits towards more animal products which results in increased demand for land allocated to food

responses. Therefore, if environmental abatement decreases food supply, food prices may increase more than proportionally, as will the marginal opportunity costs of additional abatement.

In summary, pursuing single or multiple environmental objectives alters local and supra-regional demands for LULUCF activities which in turn changes opportunity costs of land use. Increases in demand for land are highest under multiple separate, subsidy based environmental regulations. Opportunity costs are an important component for determining the likely LULUCF response to environmental policies, which is discussed in the following section.

5.2 LULUCF response to environmental regulations

How do single-policy based LULUCF responses compare to those from multiple environmental policies? First and foremost, preferred strategies are those which yield the highest net revenue under local conditions. Net revenues are the sum of market revenues and non-market net benefits over all internalized environmental attributes. Both market and non-market benefits for LULUCF measures are different under single-criterion than under multi-criteria regulations.

Let us first consider non-market impacts. As discussed in Section 4, LULUCF measures affect many environmental attributes simultaneously. In some cases, LULUCF actions could deliver “win-win” outcomes: actions that provide benefits in terms of climate change mitigation and also provide increased biodiversity and mitigation of desertification. For example, in dryland agricultural areas, reforestation can

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production. However, the emphasis here is on the “relative” (in)elasticity of demand for food relative to that of non-basic commodities (eg entertainment).

simultaneously sequester carbon, enhance biodiversity, reduce salinisation, and decrease soil erosion. Win-win options become most attractive under multi-criteria environmental regulations because incentives accumulate.

Other measures that maximise outcomes for one environmental attribute may deliver sub-optimal solutions in one or some other areas. For example, monoculture plantations may have high carbon sequestration rates, but are likely to have low biodiversity value. LULUCF measures with mixed environmental effects[9] are very attractive under single criteria policies which internalize the environmental attribute for which the measure is well-suited. Under joint environmental regulations, negative environmental impacts would be subtracted from positive ones, altering the profitability of some LULUCF measures. Enhancing productivity far in excess of the natural carbon carrying capacity[10] may not only be expensive to sustain, but may also have adverse off-site environmental and economic impacts: afforestation of grasslands may utilise freshwater lenses overlying saline groundwater, leading to land salinisation and threatening drinking water supply (Jackson et al., 2005); reduction in stream flow due to afforestation (Farley et al., 2005) may adversely impact downstream ecosystems and communities; introduction of irrigation may cause land salinisation, reduced quality of surface- and ground-water supplies for urban and rural uses, and damage to infrastructure; excessive fertilisation may cause eutrophication of waterways, impacting aquatic biodiversity and water quality for downstream users. Under joint regulation, some of these land use options may be unprofitable. For other measures with mixed effects, multi-criteria regulations could create an incentive to adapt management practices to gain

[9] That is, positive for some attributes and negative for others.
[10] Carbon stock maintained under available biophysical resources

benefits for one attribute without jeopardising another. For example, interplanting a nitrogen-fixing species with a non-N-fixing species can increase total biomass, reduce fertiliser requirements, and increase biodiversity compared with a monoculture of the non-N-fixing species (eg Forrester et al., 2005a, 2005b). Similarly, if climate policy incentives are coupled with consideration of water and nutrient balance, sustainable systems with enhanced productivity may be devised. For example, if macro and micro nutrients are added in sufficient quantity to match outputs, (offtake in product, plus losses due to volatilisation, erosion, runoff, leaching), and efforts are taken to minimise off-site impacts due to those losses, productivity of a low fertility site can be increased sustainably. Similarly, irrigation systems designed to achieve maximum water use efficiency may enhance growth rates in dry environments with minimal off-site impact. Plantations sited such that they intercept runoff from non-forested areas will achieve higher growth rates than those relying on incident rainfall and, if located appropriately, may reduce salt delivery to streams (Ellis et al., 2006).

Multi-environmental agreements also affect market profits from LULUCF measures. Price changes in response to LULUCF commodity supply shifts change the direct net revenues but also opportunity costs. Schneider, McCarl, and Schmid (2006) illustrate this complex LULUCF behaviour for hypothetical climate policies imposed on the US agricultural sector. At a low value for carbon, the optimal LULUCF response is predominantly tillage reduction to sequester soil carbon. Higher incentives lead to a double strategy. On one hand, substantial agricultural areas are diverted to perennial energy crop plantations and new forests. At the same time, the reduced area remaining in agricultural production is managed more intensively, i.e. irrigation and fertilization increases. This happens because of market price feedbacks. Afforestation and energy crop plantation decrease supply of traditional agricultural commodities and thereby cause prices to increase. Higher prices in turn promote yield intensive strategies. Thus, different policy incentives can lead to very different LULUCF responses.

5.3 Externality impacts

Externalities of environmental agreements include i) changes in the distribution of economic welfare between different segments of society, ii) impacts on other governmental policies, iii) environmental impacts on unregulated environmental goods, and iv) sub-optimal outcomes of short term decision-making. Changes in welfare distribution depend on how policy-induced land use changes affect traditional agricultural and forest production. Afforestation, perennial bioenergy crops, and expansion of nature reserves compete directly with traditional food, fibre, and timber production and decrease supply. Agroforestry, reduced tillage, and other soil preserving LULUCF measures are more complementary to traditional agricultural and forest production and, therefore, have limited supply impacts. While these impacts may be slightly negative in the short term, they could be positive in the longer term because soil conservation measures also augment productivity levels. Furthermore, production will be affected by the choice of policy instrument. Generally, environmental taxes increase the production costs of agriculture and forestry and therefore cause negative supply shifts. This is based on the assumption that the tax revenue is not returned entirely to agricultural and forest producers; responses to subsidies are opposite.

The social welfare implications of food supply shifts are complex. In the US and EU, declining agricultural commodity prices have made it more and more difficult for domestic agricultural businesses to survive without governmental support. As a result, income support policies such as the US farm bill (Sumner, 2003) or the Common Agricultural Policy (OECD, 2006) have emerged which transfer a large amount of general governmental tax money to farmers. Environmental policies that cause negative supply shifts resulting in higher commodity prices would alleviate the need for these controversial farm policies. More generally, the aforementioned relatively low elasticity of food commodity demand is likely to shift economic welfare from consumers of agricultural commodities to producers (Schneider et al., 2007). In relatively affluent societies, this redistribution is welcome because it transfers economic surplus from society as a whole to a relatively small segment of society [11] with below average income. In poor countries, rising prices for food would also increase business opportunities in the LULUCF sector but at the same time could exacerbate malnutrition for other segments of society.

Multi-environmental policies are likely to have stronger negative food supply impacts in the short term because more environmental objectives have to be met. Thus, affluent societies may favour such agreements over single-criterion policies because on top of the increased environmental gains, farmers and foresters may require less governmental support. In the longer term, food supply under multi-environmental agreements may in fact be higher than under single-criteria policies. Bioenergy policies leading to excess biomass removal may over time degrade soils and productivity. In

[11] The ratio of people working in agriculture relative to the total number of workers in some countries has decreased to less than 1:50 (calculated from FAO, 2006).

contrast, combined climate mitigation and soil preservation policies may increase future productivity.

Let us now consider the impact of environmental policies on unregulated environmental qualities. As discussed above, both positive and negative impacts are possible. Farmers adopting reduced tillage systems in response to climate policies may – depending on local conditions – deliver additional positive environmental impacts through reduced erosion, more biodiversity, and reduced nutrient leaching into rivers (Lal et al., 2004; Power et al., 2001). However, the same climate policy may trigger the replacement of a native pasture by a biomass maximizing monoculture stand with detrimental biodiversity impacts (Ranney and Mann, 1994). When comparing single and multi-criteria environmental policies, the essential question is: do the positive externalities of single criteria policies outweigh possible negative externalities? The answer is no. As argued in section 5.2, single-criterion policies offer fewer incentives to "win-win" strategies but higher incentives to strategies with negative environmental externalities. Thus, single-criterion environmental regulations are likely to generate a *cross-pollutant leakage*, i.e. benefits from regulated pollutants decrease through environmental costs from increased unregulated pollution. Nevertheless, single criteria policies may have positive environmental side effects if the reduced incentive of "win-win" strategies is still higher than the enhanced incentive of "win-loss" strategies.

Another potential externality involves *cross- regional leakage*, that is, off-site consequences of the LULUCF project: reforestation of arable land may lead to conversion of other land – forest or grazing land - to cropping in order to supply the demand for food and fibre. Cropping may be pushed onto marginal lands, requiring greater area to achieve the same yields. Thus, there may be loss of carbon stocks, increased fossil fuel emissions, and possibly loss of biodiversity, or increased risk of land degradation off-site caused by the reforestation project. Offsite leakage can occur at different scales spanning local to international ranges. Legislation limited to individual counties or states may result in negative impacts in neighbouring states, and may be easily detected. In the following example, however, leakage is indirect, and may not be identified: introduction of legislation governing land clearing in the Australian States of Queensland and New South Wales has halved emissions due to deforestation in 2004 compared with 1990 (Australian Greenhouse Office, 2006). Leakage is not immediately apparent: although rate of clearing, which is undertaken to provide land for grazing cattle, has been severely curtailed, beef production has continued to expand in Australia since 1990, at least partly due to the concomitant increase in lot feeding of cattle (Australian Bureau of Statistics, 2005). However, supply of grain to lot fed cattle requires conversion of pasture to cropland, which may increase soil erosion and increase fossil fuel use, thus increasing greenhouse gas emissions (Van der Nagel et al., 2003).

Solutions to the leakage problem exist but under current political reality are difficult to implement. Comprehensive coverage of all sectors and all countries would avoid leakage. So far, global coverage has not been achieved in any environmental arena. In the absence of such universal action, policy measures such as tariffs and restrictions on import (eg requiring certification of sustainability) can be used to reduce leakage. However, trade restrictions may be difficult to implement because they would work against the current effort to achieve trade liberalization.

Yet another externality relates to short term decision making. Landholders who care only about the near future will not worry much about long term effects of either soil degradation or soil improvements. Generally, these people are more likely to be found among land managers who rent the land rather than owning it. The extent of this externality depends on the ability to accurately assess the soil status. If soil conditions could easily be determined, land rental contracts would include provisions for maintenance of land quality. In absence of such means, political action is warranted.

6 LULUCF Governance

6.1 Guidelines for planning LULUCF measures

Reducing GHG emissions, or increasing removals, by a particular quantity of carbon dioxide equivalents will deliver equal mitigation benefit wherever it occurs, globally. In contrast, actions to mitigate biodiversity loss and desertification must be undertaken at the sites where threats are manifest, and the direct benefits will be experienced locally[12]. Although the impacts of climate change mitigation measures are experienced globally, the potential for mitigation through LULUCF activities at a particular site is dependent on the resource condition and constraints at that location. Similarly, the potential for land use measures to mitigate biodiversity loss and desertification depends on the biophysical attributes of the site. Thus, the magnitude of the benefits in terms of all three environmental objectives is dependent on the location of the action. Because the impacts of LULUCF measures are site-specific, the optimal solution to land use decisions is unique to each location.

[12] Nevertheless, there may be considerable offsite benefits from land and biodiversity preservation.

In many biophysical systems, critical thresholds have been identified; that is, relationships where the environmental outcome changes suddenly with a small change in the input (pressure) variable (Scheffer et al., 2001). These systems cannot readily recover if pushed past this threshold – the change may be irreversible, or the financial costs of remediation may be prohibitive (eg Antle et al., 200. Passing the threshold will result in a regime shift (Walker and Meyers, 2004), which can have significant implications for climate mitigation (e.g., deforestation of tropical rainforests may lead to loss of fertility and, consequently, greatly reduced capacity to maintain carbon stocks), biodiversity conservation (e.g., eutrophication of waterways may catastrophic loss of aquatic diversity) and desertification (e.g., loss of vegetative cover leading to soil erosion and loss of nutrients may prevent re-establishment of vegetation). Climate change may push natural and managed ecosystems towards critical thresholds. LULUCF measures will deliver the greatest benefits if targeted at sites that are vulnerable and responsive – that is, at systems that may be approaching but have not crossed such thresholds.

It is possible to artificially enhance productivity at a site, and therefore GHG removal, by relieving resource limitations, such as through irrigation or fertilizer application. It is also possible that exotic species can achieve greater biomass production than the natural ecosystem at a location, because the exotic species is not affected by herbivory and disease. However, it may not be desirable to seek to maximise carbon sequestration in the short term: artificially enhanced ecosystems may lack resilience and capacity to adapt; as they commonly have a narrow genetic base, exotic monocultures are vulnerable to introduction of pests and diseases, to climate variability, and to climate change. Irrigated systems may not be sustainable due to development of salinity. Afforestation/

reforestation in dry landscapes may achieve high growth rates initially while trees are able to access groundwater or moisture stored in the soil profile, but this growth rate may not be maintained when these stores are depleted and trees become reliant on incident rainfall (Harper et al., 2002). If systems are not sustainable, the environmental gains achieved will be at risk. To be sustainable, therefore, the land use systems implemented require resilience, that is, capacity to survive perturbation and adapt to change (Walker et al., 2002). Resilience is enhanced by functional redundancy, diversity and spatial heterogeneity (eg Kennedy and Smith, 1995) Resilience in agricultural and forestry systems is increased where the genetic base of each production species is broad, and where diversity of land uses produces spatial heterogeneity.

6.2 Steering LULUCF trends by policy instruments

At a national and regional level, resource management authorities have developed and implemented policy measures to promote sustainable land management, including those listed in Table 1. Policy instruments range from mandatory measures introduced through legislation that imposes penalties for non-compliance through to voluntary measures and incentive schemes. Examples of this range of instruments, as applied in the State of New South Wales, Australia, are given in Box 1.

As explained in Section 5, joint regulation is the most efficient means of meeting multiple environmental objectives. In order to facilitate land use changes that are beneficial for mitigation of desertification and conservation of biodiversity in addition to mitigation of climate change, policy instruments need to recognise multiple objectives. Policy measures may impose constraints on the outcome of land use decisions: acceptable land use options may be limited to allow only those land use changes for which predicted impacts on the target environmental attributes are neutral or positive. Where activities with negative consequences for some environmental attributes are permitted, “compensatory mitigation” (National Academy of Sciences, 2001) may be required. For example, permission to clear land may be granted under the condition that another site is reforested.

Acceptance of policy measures will govern their success, that is, the rate and scale of adoption, and the longevity of the land use change. Incentive-based policies are more likely to be embraced by landholders than command-and-control policies. Policy development that includes participation of local and distant stakeholders is also more likely to be accepted. For example, the “ecosystem approach” of the Convention on Biological Diversity considers ecological, economic, and social considerations over multiple temporal and spatial scales, and incorporates the “adaptive management" approach to on-going evaluation and modification of the implementation plan. “Participatory development”, the mechanism promoted under the UNCCD and CBD, encourages active participation in development and execution of action programmes by local communities, which is intended to build local capacity and ownership, take advantage of local knowledge and expertise in managing the local landscape, and facilitate adaptive management. The “Negotiation support model” (van Noordwijk et al., 2001) and “Resilience management” proposed by Walker et al. (2002) are based on negotiation between stakeholders, evaluation of alternative scenarios and implementation of iterative adaptive learning, to support decision-making aligned with the goal of sustainable development.

Measures that can be used to internalise the environmental costs of land use decisions include both price-based instruments, that is, taxes and subsidies, and quantity-based instruments, that is, quotas with or without tradable permits. Market-based mechanisms are generally recognised as the most effective means of internalising environmental impacts and thus encouraging change in practice by industry. Mandatory emissions trading markets have now been established in the European Union and the Australian State of NSW, and voluntary emissions trading is occurring, for example through the Chicago Climate Exchange and a rapidly growing number of emissions offset providers. The NSW and Chicago schemes allow for trading in offsets generated through a restricted range of LULUCF activities (IPART, 2006; Chicago Climate Exchange, 2006).

As explained in Section 5, introduction of a market for one environmental service may create a bias towards maximising outcomes for that attribute, to the detriment of other environmental and social objectives. For example, assessments of the impacts of CDM projects have concluded that the objective of sustainable development is suffering at the expense of low-cost emissions mitigation (e.g., Kill, 2001). On the other hand, emissions trading can provide financial support for reforestation undertaken for conservation of biodiversity and/or management of land degradation. The International Finance Corporation of the World Bank has proposed that biodiversity could be marketed in a similar fashion to carbon – with the objective of conserving resources for future exploitation to mitigate the risk of losing wealth in the form of biological resources. The demand for "biodiversity credits" would be greatly enhanced by legislation requiring their purchase, for example to offset habitat losses through urban and agricultural development. Such a policy could involve a "mitigation banking" approach analogous to that implemented under the US Clean Water Act, which facilitates compensatory mitigation in advance of authorized impacts to similar resources (US EPA, 1995).

Box: Land use policy instruments employed in NSW, Australia

The land resource management policy implemented in NSW, Australia, exemplifies a range of policy instruments that can be used together to foster sustainable land use.

Incentives: Under the NSW Environmental Services Scheme, payments have been made to landholders to support land use change: landholders' proposals were assessed on the basis of the predicted environmental benefits in terms of carbon sequestration, biodiversity impact, stream salinity, soil retention and water quality. Methods to quantify impacts on these environmental attributes were developed for the scheme, and have subsequently been incorporated into a software tool known as the Land Use Options Simulator (LUOS, Herron and Petersen, 2003). LUOS is intended as a decision support tool to be used by individual landholders and catchment management authorities for property- and region-scale land use planning, in order to direct government support to land use changes predicted to have greatest net environmental benefit. (Forests NSW, 2004)

Penalties: NSW Native Vegetation Act 2003 regulates clearing of native vegetation and imposes severe financial penalties for non-compliance. Applications for clearing are assessed using a software tool (Property Vegetation Plan Developer) that predicts the impact of clearing on biodiversity, including threatened species, salinity, water quality, land and soil conservation and invasive native species. Land uses changes that are predicted to deliver a negative outcome for any of these environmental attributes are not permitted. (NSW Government, 2005)

Offsets: Removal of small forest patches or individual trees are allowed under the Native Vegetation Act in some circumstances under the condition that a substantial area of native vegetation is established elsewhere.

Market-based mechanism: The NSW Greenhouse Gas Abatement Scheme imposes mandatory emission limits on all NSW electricity retailers and some large electricity users. The scheme allows targets to be met through a variety of measures including carbon sequestration in eligible forestry activities. (IPART, 2006)

Guidance: Recent legislative changes have devolved responsibility for natural resource management to regional Catchment Management Authorities that operate within guidelines developed by the NSW Natural Resources Commission. The NRC sets standards and targets for vegetation retention or revegetation, soil management, salinity, threatened species, wetlands and coastal estuaries. CMAs develop catchment action plans to meet these targets, and utilise LUOS to guide investment in land use change to achieve multiple objectives – to meet the targets specified by the NRC, to manage vegetation clearing as required by legislation, and to plan reforestation that delivers carbon sequestration and generates offset credits through the NSW Greenhouse Gas Abatement Scheme.

End box

7 Conclusions

Land use, land use change and forestry impact greenhouse gas emissions, biodiversity, and soil and water quality. Left unregulated, LULUCF respond optimally to current market demands for food, fibre, fuel, and timber but fail to acknowledge the above named environmental externalities. Consequently it is critical that national and international environmental policy is developed to manage these externalities. This paper argues that this process should be jointly pursued for all major environmental goals and not independently as is the dominating current practice. The arguments discussed in this paper can be summarised in seven major points.

First, choice of land use, from among the numerous alternatives, affects climate, biodiversity, and land quality simultaneously. Second, land is scarce and many land use decisions are mutually exclusive. Therefore, land use changes aimed solely at meeting the goal of one environmental convention are likely to reduce the potential to meet goals of the other conventions. Third, the land use strategies implemented to pursue the goals of the three conventions can be complementary; land use decisions that may deliver the greatest simultaneous benefit for all three environmental objectives are reforestation, avoided deforestation and avoided degradation. However, tradeoffs are also likely. Pursuing the environmental goals of these conventions individually may promote unsustainable land uses which cause unnecessary harm in other environmental areas. Fourth, opportunity costs of land are heterogeneous, as are the local soil, climate, and market conditions. Only joint implementation of the environmental conventions ensures that this heterogeneity is adequately internalized and gives appropriate incentives and disincentives.

Fifth, implementation of policy incentives to promote environmental goals may have a higher cost if each goal is pursued independently because tradeoffs and complementarities are ignored. Sixth, the optimal LULUCF pattern under a joint policy setting can differ substantially from the LULUCF pattern under individually-implemented policies. These differences may involve the regional balance between forestry, agriculture, and nature reserves, and management related to species choice and production intensity. Seventh, environmental policy goals may alleviate the need for existing agricultural subsidies. Huge governmental payments through farm income support policies in the US, Europe, and other countries could be saved by internalizing the environmental cost of agricultural production.

Within the current negotiation cycle for the UNFCCC, CBD and UNCCD there may be the option for a joint implementation protocol for LULUCF that may include common measures that are beneficial to the achievement of the goals of all three conventions. Policy that promotes change in land use patterns towards sustainable land management is the most effective way forward towards mitigating negative climate change trends, preserving biodiversity and fighting desertification.

Several alternative accounting approaches for land use and land use change, suggested for consideration in the development of the policy framework for a future climate agreement, are presented in other papers in this volume. We should take advantage of the impetus to address climate change to ensure that LULUCF policy promotes optimal outcomes for environmental integrity and sustainable development.

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References

Adams, J.M., Faure, H. (1997) - Preliminary vegetation maps of the world since the Last Glacial Maximum: an aid to archaeological understanding. - Journal of Archaeological Science 24, 623-647

Adl S., Coleman, D.C., Read, F. 2006. Slow recovery of soil biodiversity in sandy loam soils of Georgia after 25 years of no-tillage management. Agriculture, Ecosystems and Environment 114, 323–334.

Antle, J.M., Stoorvogel , J.J., Valdivia, R.O. 2006 Multiple equilibria, soil conservation investments and the resilience of agricultural systems. Environment and Development Economics, 11, 477-492

Arnalds, O., 2005. Knowledge and policy making; Premises, paradigms, and a Sustailability Index Model. Strategies, Scicen and law for the Conservation of the World Soil Resources. International Workshop Selfoss, Iceland September 14-18, 2005. Agricultural University of Iceland. pp 251-259.

Arrow, K., Dasgupta, P., Mäler, K.-G., 2003. Evaluating Projects and Assessing Sustainable Development in Imperfect Economies. "International Conference on Theoretical Topics in Ecological Economics", Trieste, Italy, February 10-12, 2003. Available at: http://www.feem.it/NR/rdonlyres/D546AC56-0847-4AD6-805A-84F387DB0A7C/971/10903.pdf

Ashby, J. A. 2001. Integrating research on food and the environment: an exit strategy from the rational fool syndrome in agricultural science. Conservation Ecology 5(2): 20. [online] URL: http://www.consecol.org/vol5/iss2/art20/

Australian Bureau of Statistics, 2005. Australia's beef cattle industry Year Book Australia , 2005. Chapter 14 Agriculture. Australian Bureau of Statistics.

Australian Greenhouse Office, 2006. National Greenhouse Inventory 2004: Accounting for the 108% target. Australian Government Department of the Environment and Heritage Australian Greenhouse Office http://www.greenhouse.gov.au/inventory/2004/pubs/inventory2004.pdf

Börjesson, P., Gustavsson, L., 2000. Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives. Energy Policy 28, 575-588.

Brown K., Corbera E., 2003. Exploring equity and sustainable development in the new carbon economy Climate Policy 3S1S41–S56

Brown D.J., Shepherd, K.D., Walsh, M.G., Mays, M.D., Reinsch, T.G. 2006 Global soil characterization with VNIR diffuse reflectance spectroscopy. Geoderma 132 , 273–290

Buckingham, D.L., Peach, W.J., Fox, D.S., 2006. Effects of agricultural management on the use of lowland grassland in the UK by foraging birds. Agriculture, Ecosystems and Environment 112, 21-40.

CBD, undated The Rio Conventions Joint Liaison Group http://www.biodiv.org/cooperation/liason.shtml

CBD, 2003. Interlinkages between biological diversity and climate change Advice on the integration of biodiversity considerations into the implementation of the United Nations Framework Convention on Climate Change and its Kyoto Protocol Montreal, SCBD, 154p. (CBD Technical Series no. 10).

Chicago Climate Exchange 2006. CCX Forestry Carbon Emissions Offsets. http://www.chicagoclimatex.com/news/publications/pdf/CCX_Forest_Offsets.pdf

Cleveland, C.C. and Townsend, A.R., 2006. Nutrient additions to a tropical rain forest drive substantial soil carbon dioxide losses to the atmosphere. Proceedings of the National Academy of Sciences of the United States of America 103, 10316-10321.

Cowie A.L., Smith, P., Johnson, D., 2006. Does soil carbon loss in biomass production systems negate the greenhouse benefits of bioenergy? Mitigation and Adaptation Strategies for Global Change 11, 979-1002.

Crowley T. J., 1995. Ice age terrestrial carbon changes revisited. Global Biogeochemical Cycles 9, 377-389.

Crutzen PJ 2002. Geology of mankind. Nature 415, 23

Diamond, J., 1999. Guns, Germs, and Steel: The Fates of Human Societies. New York: Norton Press.

Ellis, T. W. Legu´edois, S. Hairsine, P. B. and Tongway D. J. 2006 Capture of overland flow by a tree belt on a pastured hillslope in south-eastern Australia. Australian Journal of Soil Research, 44, 117–125.

Emery, K.A. 1985. Rural Land Capability Mapping. Soil Conservation Service of NSW, Sydney.

Food and Agriculture Organization of the United Nations (FAO), 2006. FAOSTAT. Statistics database. http://faostat.fao.org/

Farley K.A., Jobbagy, E.G., Jackson, R.B., 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. Global Change Biology 11, 1565–1576,

Farrell, A.E., Plevin, R.J., Turner, B.T., Jones, A.D., O'Hare, M, Kammen, D.M. 2006. Ethanol can contribute to energy and environmental goals. Science. 311, 506-508.

Fearnside, P., 2001. The Potential of Brazil"s Forest Sector for Mitigating Global Warming under the Kyoto Protocol Mitigation and Adaptiation Strategies for Global Change 6, 355-372.

Food and Agriculture Organization (FAO) 1992. Forests, trees and food. Food and Agriculture Organization of the United Nations. http://www.fao.org/docrep/006/U5620E/U5620E00.HTM

Forests NSW 2004. Environmental Services Scheme. NSW Department of Primary Industries. http://www.forest.nsw.gov.au/env_services/ess/default.asp

Forrester, D.I., Bauhus, J., Cowie, A.L., 2005a.Nutrient cycling in a mixed-species plantation of *Eucalyptus globulus* and *Acacia mearnsi*. Canadian Journal of Forest Research. 35(12): 2942-2950

Forrester, D.I., Bauhus, J., Cowie, A.L., 2005b. On the success and failure of mixed-species tree plantations: lessons learned from a model system of *Eucalyptus globulus* and *Acacia mearnsi*. Forest Ecology and Management 209, 147-155.

Freudenberger, D., Harvey, J., 2003. Case Study Applications of a Draft Framework for Assessing the Biodiversity Benefits of Vegetation Enhancement Activities. Department of Environment and Heritage. Available at: http://www.deh.gov.au/land/publications/application/index.html#pdf

Gibbons, P., Ayers, D., Seddon, J., Doyle, S. and Briggs, S. (2005). BioMetric Version 1.8. A Terrestrial Biodiversity Assessment Tool for the NSW Property Vegetation Plan Developer: Operational Manual. NSW Department of Environment and Conservation. http://www.nationalparks.nsw.gov.au/PDFs/BioMetric_manual_v1_8.pdf

Gisladottir, G., Stocking, M., 2005. Land Degradation Control and its Global Environmental Benefits. Land Degradation and Development 16:2, 99-112.

Goudkamp, J., Lam, S., Wong, K., Wardle, G., 2003. Salinity impacts and risks to biodiversity in Australia PUR$L National Conference: Salinity under the sun - investing in prevention and rehabilitation of salinity in Australia. http://www.ndsp.gov.au/downloads/pdfs/Pursl2003_2_op_Goudkamp_Jacqueline.pdf

Guo, L.B. and Gifford, R.M.: 2002, ‘Soil carbon stocks and land-use change: A meta analysis’, Global Change Biology 8, 345-360.

Gupta, R.K., Rao, D.L.N., 1994. Potential of Wastelands for Sequestering Carbon by Reforestation. Current Science, 66, 378-380.

Harper, R.J., McGrath, J.F., Carter, J.O., 2002. A pedo-geomorphic approach for predicting drought deaths in Eucalyptus globulus (Labill.) plantations. 17th World Council Soil Science 14-21 August 2002, Thailand Symposium no. 40 Paper no. 1745. 1745-1to 1745-10.

Herron N., Peterson, P., 2003. A Simplified GIS-Based Approach to Prioritise Salinity Investment at the Property-Scale. Proceedings MODSIM 2003 International Congress on Modelling and Simulation, 14-17 July 2003, Townsville. Modelling and Simulation Society of Australia and New Zealand. Available at: http://www.dlwc.nsw.gov.au/salinity/science/pdf/herron_peterson_2003.pdf

Houghton, J.T., Meira Filho, L.G., Lim, B., Tréanton, K., Mamaty, I., Bonduki, Y., Griggs, D.J. and Callander, B.A. (eds), 1997. Revised 1996 IPCC guidelines for national greenhouse gas inventories. Intergovernmental Panel on Climate Change, Meteorological Office, Bracknell, United Kingdom. Volume 1: Greenhouse gas inventory reporting instructions. 130 pp. Volume 2: Greenhouse gas inventory workbook. 346 pp. Volume 3: Greenhouse gas inventory reference manual. 482 pp. http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm

Huston, M., 1993. Biological diversity, soils and economics. Science 262, 1676-1680.

IPART (Independent Pricing and Regulatory Tribunal of New South Wales) 2006 Introduction to the Greenhouse Gas Abatement Scheme (GGAS). 16 pp. http://www.greenhousegas.nsw.gov.au/documents/Intro-GGAS.pdf

IUCNN (International Union for the Conservation of Nature and Natural Resources), United Nations Environment Program and World Wildlife Fund. 1991. Caring For the Earth. A Strategy for Sustainable Living. Gland. Switzerland.

Jackson, R.B., Jobbagy, E.G., Avissar, R., Roy SB, Barrett DJ, Cook CW, Farley KA, le Maitre DC, McCarl BA, Murray BC. 2005. Trading Water for Carbon with Biological Carbon Sequestration Science 310: 1944-1947

Jacobsen, T., Adams, R.M., 1958. Salt and Silt in Ancient Mesopotamian Agriculture. Science Vol. 128, No.3334, 21 November 1958, p.1252.

Janik, L.J., Merry, R.H. and Skjemstad, J.O., 1998. Can mid infrared diffuse reflectance analysis replace soil extractions?. Australian Journal of Experimental Agriculture 38, 681-696.

Kavanagh, R, Law, B., Lemckert, F, Stanton, M, Chidel, M, Brassil, T., Towerton, A., Herring, M., 2005. Biodiversity in eucalypt plantings established to reduce salinity. Rural Industries Research and Development Corporation, Publication No 05/165. RIRDC Canberra, Australia. 81pp

Kennedy, A.C., Smith, K.L. 1995. Soil microbial diversity and the sustainability of agricultural soils. Plant and Soil. 170, 75-86.

Kill, J., 2001. Sinks in the Kyoto Protocol. A dirty deal for forests, forest people and climate. Fern, Brussels. 19pp. http://www.fern.org/pubs/briefs/sinks2.pdf

Kurz, W., Apps, M. 2006. Developing Canada's National Forest Carbon Monitoring, Accounting and Reporting System to Meet the Reporting Requirements of the Kyoto Protocol Mitigation and Adaptation Strategies for Global Change, 11, 33-43.

Lal R., Griffin M., Apt J,. Lave, L., Morgan, M. 2004. Ecology - Managing soil carbon Science 304 (5669), 393-393.

Lowdermilk, W. C. 1953. Conquest of the Land Through 7,000 Years. Bulletin 99. Washington, D.C.: U.S. Department of Agriculture, Soil Conservation Service. p30

MacCleery, D. 1999. Understanding the role that humans have played in shaping America's forest and grassland landscapes: Is there a landscape archaeologist in the house? Landscapes. USDA Forest Service. 2/25/99:1-14.

MacDicken K.G. (1997). A Guide to Monitoring Carbon Storage in Forestry and Agroforestry Projects.Winrock International, Arlington, VA, USA, 87 pp, available at: http://v1.winrock.org/reep/pdf_pubs/carbon.pdf

MacNeill, J. 1989. Strategies for Environment and Development, Our Common Future. In, Future, Commission for the Future, 12:11.

Masera, O., Garza-Caligaris, J.F., Kanninen, M., Karjalainen, T., Liski, J., Nabuurs, G.J., Pussinen, A. & de Jong, B.J. 2003. Modelling carbon sequestration in afforestation, agroforestry and forest management projects: the CO2FIX V.2 approach. Ecological Modelling 164: 177-199.

Marland, G. and Schlamadinger, B., 1997. Forests for carbon sequestration or fossil fuel

substitution? A sensitivity analysis. Biomass and Bioenergy 13, 389-397.

Mazoyer M, Roudart, L 1997 Histoire des agricultures du monde:Du néolithique à la crise contemporaine Seuil p533

Millennium Ecosystem Assessment (MA), 2003: Ecosystems and Human Well-Being: A Framework for Assessment. Island Press, Washington, DC, 245 pp.

Millennium Ecosystem Assessment 2005a Ecosystems and human well-being: Vol 1 Current state and trends: Findings of the Condition and Trends Working Group Millennium Ecosystem Assessment Series 815p Chapter 22: Dryland Systems

Millennium Ecosystem Assessment, 2005b Ecosystems and human well-being: Vol 4 Multiscale assessments Island Press 515p.

Montagnini F., Nair, P.K.R., 2004. Carbon sequestration: An underexploited environmental benefit of agroforestry systems. Agroforestry Systems 61-62, 281 – 295.

Muller S., 2002. Appropriate agricultural management practices required to ensure conservation and biodiversity of environmentally sensitive grassland sites designated under Natura 2000. Agriculture, Ecosystems and Environment 89, 261-266.

National Academy of Sciences, 2001.Compensating for Wetland Losses Under the Clean Water Act. National Academy Press. Washington, D.C. http://newton.nap.edu/execsumm_pdf/10134.pdf

NSW Government 2005. Native Vegetation Regulation 2005 Environmental Outcomes Assessment Methodology http://www.nativevegetation.nsw.gov.au/p/eoamv4_14.pdf

NSW Independent Pricing and Regulatory Tribunal, undated. NSW Greenhouse Gas Abatement Scheme. http://www.greenhousegas.nsw.gov.au/

Organisation for Economic Co-operation and Development (2006) Agricultural Policies in OECD Countries at a Glance: 2006 Edition, OECD Publishing

Oliver I and Parkes D 2003 A prototype toolkit for scoring the biodiversity benefits of land use change. Version 5.1 NSW Department of Infrastructure, Planning and Natural Resources, Parramatta. P40.

Paul, K.I., Polglase, P.J., Nyakuengama, J.G. and Khanna, P.K., 2002. Change in soil carbon following afforestation. Forest Ecology and Management 168, 241-257.

Penman, J., Gytartsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti R., Buendia, L., Miwa K, Ngara, T., Tanabe K., Wagner F. (eds.), 2003. Good Practice Guidance For Land Use, Land-Use Change and Forestry, Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme, Institute for Global Environmental

Strategies (IGES), Kanagawa, Japan, pp.3.1-3.312. www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm

Pingoud, K.,, Perälä, A.L., Soimakallio, S., Pussinen, A. 2003. Greenhouse gas impacts of harvested wood products. Evaluation and development of methods. Espoo. VTT Tiedotteita . Research Notes 2189. 120 p. + app. 16 p.

Power J. F., R. Wiese, and D. Flowerday 2001. Managing Farming Systems for Nitrate Control: A Research Review from Management Systems Evaluation Areas. J. Environ. Qual. 30, 1866–1880.

Ranney, J. W., Mann, L. K., 1994. Environmental Considerations in Energy Crop Production. Biomass and Bioenergy 6, 211-228.

Richards, G.P., and Evans D.W. 2004. Development of the FullCAM Carbon Accounting Model, (FullCAM vers. 1.0) for the Australian Continent. Australian Forestry 67, 277-283.

Robinson, N., Harper, R.J., Smettem, K.R.J., 2006. Soil water depletion by *Eucalyptus* spp. integrated into dryland agricultural systems. Plant and Soil 286, 141-151.

Rodríguez, J.P., Beard, T.D., Bennett, E.M., Cumming, G.S., Cork, S.J., Agard, J., Dobson, A.P., Peterson, G.D. 2006. Trade-offs across space, time, and ecosystem services. Ecology and Society 11(1): 28. [online] URL: http://www.ecologyandsociety.org/vol11/iss1/art28/

Sampson, N., Scholes, R., Cerri, C. Erda, L. Hall, D.O. Handa, M. Hill, P. Howden, M. Janzen, H. Kimble, J. Lal, R. Marland , G. Minami, K. , Paustian, K. Read, P. Sanchez, P.A. Scoppa, C. Solberg, B. Trossero, M.A. Trumbore, S. Van Cleemput, O. Whitmore,

A. Xu D. 2000. Chapter 4, Additional Human-Induced Activities - Article 3.4, In Land Use, Land-Use Change, and Forestry. A Special Report of the IPCC, 181-281.

Scheffer, M., Carpenter, S., Foley, J.A., Folkes, C., Walker, B. 2001. Catastrophic shifts in ecosystems. Nature 413, 591-596.

Schneider, U. A. and Mccarl, B. A. (2006). Appraising agricultural greenhouse gas mitigation potentials: Effects of alternative assumptions. Agricultural Economics. 35, 277-287.

Schneider, U. A., Mccarl, B. A., and Schmid, E. (2007). Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry. Agricultural Systems. (In press)

Sheehan, J., Camobreco, V., Duffield, J., Graboski, M., Shapouri, H. 1998. Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus. National Renewable Energy Laboratory. 286pp. http://www.nrel.gov/docs/legosti/fy98/24089.pdf

Stirzaker, R., Vertessy, R. and Sarre, A. 2002 Trees, water and salt: an Australian guide ti using trees for healthy catchmnts and productive farms. Joint Venture Agroforestry Program Rural Industries Research and Development Corporation publication 01/086 RIRDC Canberra, Australia. 159pp

Sumner, D. A. (2003). Implications of the US Farm Bill of 2002 for agricultural trade and trade negotiations. Australian Journal of Agricultural and Resource Economics 47, 99-122.

United Nations, 1992a. Convention on Biological Diversity. http://www.biodiv.org/convention/articles.asp

United Nations, 1992b. The Rio Declaration. United Nations Environment Programme http://www.unep.org/Documents.multilingual/Default.asp?DocumentID=78&ArticleID=1163

United Nations, 1992c. Agenda 21. United Nations Department of Economic and Social Affairs Division for Sustainable Development http://www.un.org/esa/sustdev/documents/agenda21/english/agenda21toc.htm

United Nations, 1994. Convention to Combat Desertification. http://www.unccd.int/

United Nations Convention to Combat Desertification (UNCCD), 2004. Forests and Forest Ecosystems: Promoting Synergy in the Implementation of the Three Rio Conventions. Workshop presentations and report available at: http://www.unccd.int/workshop/menu.php

United Nations Environment Programme (UNEP), 1982. World Charter for Nature.

United Nations Environment Programme (UNEP), 1991. Implementation of The Plan of Action to Combat Desertification. http://grid2.cr.usgs.gov/des/desfintoc.php3

United Nations Conference on the Human Environment, 1972. Declaration of the United Nations Conference on the Human Environment, Stockholm, 1972.

United Nations Forum on Forests (UNFF), undated. http://www.fao.org/forestry/foris/webview/cpf/index.jsp?siteId=1220&sitetreeId=2080&langId=1&geoId=0

United Nations Framework Convention on Climate Change (UNFCCC), 2004. Options for enhanced cooperation among the three Rio Conventions. FCCC/SBSTA/2004/INF.19 http://unfccc.int/resource/docs/2004/sbsta/inf19.pdf

United States Department of Agriculture (USDA), 1999 and 2003. Environmental Benefits Index Conservation reserve Program Sign-Up 20 Farm Services Agency 6p. http://www.fsa.usda.gov/pas/publications/facts/ebiold.pdf and http://www.fsa.usda.gov/pas/publications/facts/crpebi03.pdf

United States Environmental Protection Agency (US EPA), 1995. Federal Guidance for the Establishment, Use and Operation of Mitigation Banks 60 Fed. Reg. 228, 58605-58614. http://www.epa.gov/owow/wetlands/guidance/mitbankn.html

Vagen, T-G., Lal, R, Singh, B.R., 2005. Soil carbon sequestration in sub-Saharan Africa: a review. Land Degradation and Development, 16, 53–71.

Van der Nagel L., Waghorn G.C., Forgie V., 2003. Greenhouse gas emissions from cows fed pasture or concentrate. Proceedings of the Dairy3 Conference. 2, 99-102.

van Noordwijk, M., T. P. Tomich, B. Verbist. 2001. Negotiation support models for integrated natural resource management in tropical forest margins. Conservation Ecology 5(2): 21. [online] URL: http://www.consecol.org/vol5/iss2/art21/

Walker, B., Carpenter, S., Anderies, J., Abel, N., Cumming, G., Janssen, M., Lebel, L., Norberg, J., Peterson, G.D., Pritchard, R. 2002. Resilience management in social-ecological systems: a working hypothesis for a participatory approach. Conservation Ecology 6(1):14. 17pp [online] URL: http://www.consecol.org/vol6/iss1/art14/

Walker, B., J. A. Meyers., 2004. Thresholds in ecological and social–ecological systems: a developing database. Ecology and Society 9(2): 3. [online] URL: http://www.ecologyandsociety.org/vol9/iss2/art3/

Wirtz, K.W., Lemmen, C.,2003. A global dynamic model for the Neolithic Transition. Climatic Change 59, 333-367.

The World Commission on Environment and Development (WCED), 1987. Our Common Future, Oxford University Press.

Yibarbuk D, Whitehead PJ, Russell-Smith J, Jackson D, Godjuwa C, Fisher A, Cooke P, Choquenot D, Bowman D (2001) Fire ecology and Aboriginal land management in central Arnhem Land, northern Australia: a tradition of ecosystem management. Journal of Biogeography, 28, 325-343.

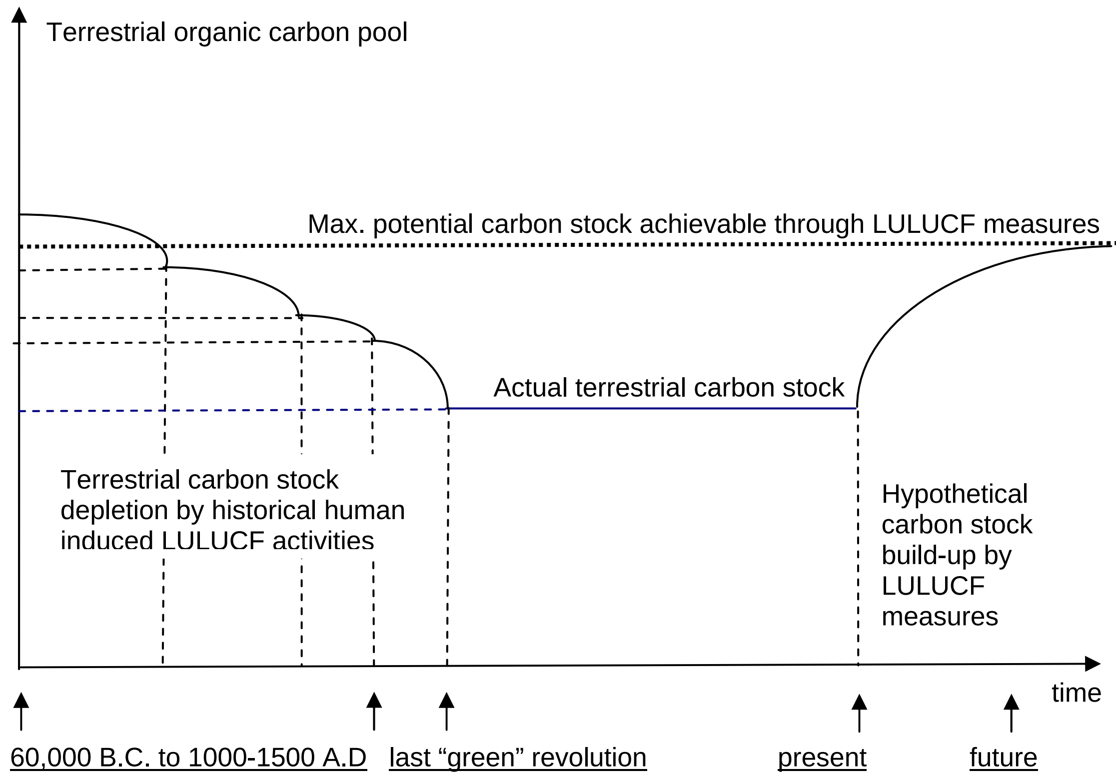

Figure 1: Simplified representation of the dynamics of the terrestrial organic carbon pool over time.

Table 1: Global environmental and sustainable development agreements that impact on LULUCF activities and examples of regional and national policies enacted to implement these agreements

Global treaties, conventions, etc	Regional Agreements (Examples)	National/State strategies, policies (Examples)
Climate change		
United nations framework convention on climate change (1992/1994)[1] Kyoto Protocol (1997/2005)	European Climate Change Programme (2000) EU Emissions Trading Scheme EU Renewable Energy target 2010 EU Energy crop subsidy Asia Pacific Partnership on Clean Development and Climate 2006	UK Climate Change Programme New South Wales Greenhouse Gas Abatement scheme (Australia)\ Regional Greenhouse Gas Initiative (NE States USA) National renewable energy targets (eg USA, Canada, Brazil, Australia, UK Renewables Obligation) National programs for reforestation (e.g., Canada, New Zealand, Ireland)
Biodiversity		
Convention on Wetlands (Ramsar, 1971/1975) Convention Concerning the Protection of World Cultural and Natural Heritage (1972/1975) Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973/1975) World Conservation Strategy IUCN/UNEP/WWF 1980 UN World Charter for Nature 1982 Convention on Migratory Species (Bonn, 1979/1983) UN Convention on Biological Diversity (1992/1993) Cartagena Protocol On Biosafety (2001/2003)	The Convention on the Conservation of European Wildlife and Natural Habitat (Bern Convention, 1982) European Conservation Strategy 1990 EC Biodiversity Strategy 1998 Pan-European Biological and Landscape Diversity Strategy	National policies on conservation of Biodiversity and protection of threatened species (e.g. Australia, New Zealand) Legislation controlling land clearing (e.g., Queensland and New South Wales, Australia) National Biodiversity Action Plans (Parties to the CBD)
Desertification/Land degradation		
Plan of Action to Combat Desertification 1977 World Soils Policy UNEP 1980 World Soil Charter FAO1981 United Nations Convention to Combat Desertification (1994/1996)	European Landscape Convention 2000/2004	Soil conservation policies (eg Iceland, Australia, New Zealand, USA) Farm income support/Rural adjustment eg US Farm program; The Canadian Agricultural Income Stabilization (CAIS) Program; Agriculture Advancing Australia Conversion of cropland to forest program (China) National water initiative (Australia) National Action Programmes – Parties to the UNCCD Desertification prevention and control law (China)
Sustainable development		
Agenda 21 1992 Millennium Development Goals 2000 World Summit for Sustainable Development Johannesburg Declaration 2002	EC Environmental Action Programmes,1993, 2002 EU Sustainable development strategy	Local Agenda 21 Eg Canada: Sustainable Development Technology Fund

Table 2: LULUCF measures proposed for climate change: their likely impact on climate change, biodiversity and desertification. Positive and negative trends are indicated by + and -, respectively. The significance of the impact increases from 0 (no impact), + or - (minor impact) to +++ or ---(large impact).

Land use change	**Climate change**	**Biodiversity**	**Desertification**
Conversion from conventional cropping to:			
Reduced tillage	Increase or no change in SOC 0-+ Decreased fossil fuel use +	Increased biodiversity in soil depending on herbicide use +	Reduced erosion + increased water holding capacity +
Crop residue retention	Increased SOC ++	Increased soil biodiversity ++	Improved soil fertility + reduced erosion ++ increased water holding capacity +
Perennial pasture and permanent crops	Increased SOC ++ increased biomass 0-++ Leakage: Decreased biomass and SOC on other land converted to arable - - to -	Minor; dependent on species + to ++ Leakage: Decreased biodiversity on other land converted to arable - - to -	Reduced erosion, ++ Increased infiltration and water holding capacity +
Organic amendments such as manure, compost, mulch, biosolids	Increased SOC + to +++	Possible increase in soil biodiversity, or decrease if amendments are contaminated eg with heavy metals – to ++	Improved soil fertility +++ reduced erosion + increased water holding capacity ++
Improved rotations e.g. green manure, pasture phase, double cropping (no fallow)	Increased SOC +	increased soil biodiversity, and above ground biodiversity +	Improved soil fertility + increased water holding capacity +
Fertilisation	Increased biomass + to ++ Increased N_2O emissions - - to - GHG costs of chemical fertiliser production -	Possible negative offsite impact on native, especially aquatic, species --	Increased fertility increases land cover +++ Some fertilisers e.g. ammonium salts can cause acidification -
Irrigation	Increased biomass + GHG costs of pumping irrigation water - Increased fertiliser use - Higher N_20 emissions - Salinisation may cause off-site loss of biomass - Off-site carbon gains because less land is needed for food crops and more land can be allocated to renewable energy or afforestation + to ++	Impact dependent on the land use system displaced, but may include loss of native remnants, reduced diversity of crop species - - to 0 Salinisation may cause off-site loss of biodiversity - - to - Off-site biodiversity gains because less land is needed for agriculture and more land can be allocated to conservation reserves + to ++	Increased productivity but high risk of soil salinisation --- to +
Bioenergy crops	Displacement of fossil fuels +++ Impact on biomass dependent on bioenergy	Impact on biodiversity dependent on bioenergy crop species: annual crops 0	Dependent on bioenergy crop species; Strategic establishment of perennial bioenergy crops may

	crop species: annual crops - to 0 perennial woody crops + to ++ Increased biomass removal may reduce SOC - to 0 Increased fertiliser requirements to replace additional nutrients removed -	perennial woody crops + to ++	increase land cover, reduce salinity + Increased removal of biomass in annual bioenergy crops may reduce soil protection and increase removal of SOC -
Organic farming	Possibly higher SOC 0 to + Leakage: Lower yield per ha so more area required: Decreased biomass on other land converted to arable - - to -	Increased on-site biodiversity (no pesticides) + Leakage: Lower yield per ha so more area required: - - to -	Increased SOM reduces erosion, increases water holding capacity + Leakage: Lower yield per ha so more area required: - - to -
Reforestation to plantation	Increased biomass +++ Potential leakage - Decreased biomass and SCO if other land converted to arable; impact dependent on C stock of other land - - to -	Biodiversity increase above ground and belowground ++ Potential leakage - Decreased biodiversity off-site if other land converted to arable - - - to - Reduced streamflow - -	Reduced wind and water erosion +++ Reduction in dryland salinity ++
Afforestation/Reforestation to native forest/woodland	Increased biomass ++ Increased SOC ++ Decreased fossil fuel use + Potential leakage - Decreased biomass and SOC increased GHG emissions if other land converted to arable; impact dependent on C stock of other land - - to -	Biodiversity increase above ground and belowground +++ Potential leakage - Decreased biodiversity off-site if other land converted to arable - - - to - Reduced streamflow -	Reduced wind and water erosion +++ Increased transpiration reduces dryland salinity ++
From conventional grazing to:			
Higher productivity pasture species – eg convert annual to perennial species, add legume	Increased biomass + Increased SOC ++ Reduced CH4 from enteric fermentation due to higher quality feed +	May increase plant biodiversity 0 to + Increase in bg biodiversity +	Increased land cover reduces erosion ++
Conservative grazing/Cutting method and frequency	Increased biomass and SOC +	Protects species sensitive to over-grazing +	Increased land cover, reduced compaction reduces erosion ++
Fertilisation	Increased biomass and SOC +-++	Possible negative impact on native grasslands -- to 0	Increased productivity increases land cover ++
Afforestation/reforestation	SOC may increase or decrease depending on relative productivity - to + Increased biomass +++	Impact dependent on the pasture system replaced, and forest type but may include loss of native	Increased transpiration reduces dryland salinity ++

	Leakage: Decreased biomass and SOC on forested land converted to grazing - - to -	grasslands - - to --	Reduced wind erosion +-+++
Bioenergy crops	Displacement of fossil fuels +++ Impact on biomass dependent on bioenergy crop species: annual crops 0 to - perennial woody crops + to ++ Reduced SOC due to increased biomass removal and soil disturbance, especially for annual crops - - to - Increased fertiliser requirements to replace additional nutrients removed -	Impact on biodiversity dependent on pasture system replaced and bioenergy crop species: annual crops - perennial woody crops + to ++ If native grasslands replaced --	Impact dependent on bioenergy crop species: Tillage reduces land cover, increases soil erosion annual crops - - to - perennial woody crops – to 0
Forest management			
Irrigation or fertilisation	Increased biomass + Increased SOC +	May inhibit native species -	Increased cover and SOC + Potential for salinisation - -
Extend rotation	Increased average carbon stock in biomass and SOC + to ++	Enhanced onsite biodiversity ++	Less frequent soil disturbance +
Protection against deforestation/degradation	Avoids loss of biomass and SOC +++	Protects biodiversity +++	Prevents degradation +++

The European Forest and Agricultural Sector Optimization Model - EUFASOM

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The European Forest and Agricultural Sector Optimization Model - EUFASOM

Keywords

Land Use Change Optimization, Resource Scarcity, Market Competition, Welfare Maximization, Bottom-up Partial Equilibrium Analysis, Agricultural Externality Mitigation, Forest Dynamics, Global Change Adaptation, Environmental Policy Simulation, Integrated Assessment, Mathematical Programming, GAMS

EAERE codes

* Resources and Ecosystem Studies: Forest resources
* Agriculture: Agri-environmental policy
* Resources and Ecosystem Studies: Climate change
Resources and Ecosystem Studies: Energy issues
Resources and Ecosystem Studies: Biodiversity
Resources and Ecosystem Studies: Soil; Soil erosion

Abstract

Land use is a key factor to social wellbeing and has become a major component in political negotiations. This paper describes the mathematical structure of the European Forest and Agricultural Sector Optimization Model. The model represents simultaneously observed resource and technological heterogeneity, global commodity markets, and multiple environmental qualities. Land scarcity and land competition between traditional agriculture, forests, nature reserves, pastures, and bioenergy plantations is explicitly captured. Environmental change, technological progress, and policies can be investigated in parallel. The model is well-suited to estimate competitive economic potentials of land based mitigation, leakage, and synergies and trade-offs between multiple environmental objectives.

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The European Forest and Agricultural Sector Optimization Model

Introduction and Literature

Land use is a key factor to social wellbeing and has become a major component in political negotiations. Land use affects food supply, employment, energy security, water, climate, and ecosystems. Over the last few decades, technical progress and intensifications have ensured a large increase in food supply (Briunsma, 2003) enough to potentially eradicate malnutrition. However, projected population developments and their impacts on demand for food, land, energy, and water as well as feedbacks of environmental change may put additional pressure on food production technologies in the next decades.

The food and fiber production achievements of past decades in the agricultural and forest sectors have taken a toll on the environment. Particularly, these sectors are blamed for contributions to greenhouse gas emissions, ecosystem destruction and associated biodiversity losses, water shortage and contamination, and land degradation. On the other hand, land use changes in agriculture and forestry are considered as potential remedies to environmental problems (Smith et al. 2008).

The European Union has formulated ambitious objectives regarding bioenergy production, reduction of greenhouse gas emissions, and biodiversity protection (European Economic Community 1992, European Union 2003; Commission of the European Communities 2008). By 2020, the EU has committed to a reduction by at least 20% of its total greenhouse gas emissions relative to 1990 levels, a 20% share of renewable energies in its energy production, and a 10% share of biofuels in its petrol and diesel consumption. Meeting these targets will involve significant impacts on land use and land use management. These developments have raised questions regarding their effects on agricultural and forestry products markets and competition for land between forestry, food and non-food agriculture. Concern has also been growing regarding the net environmental impacts of these changes and the potential sources of leakage (for example through intensification of agricultural production leading to increased agricultural emissions or international displacements of emissions through deforestation, e.g. Rajagopal, D. & Zilberman, D. 2007). Therefore, integrated modeling approaches are needed to tackle these issues.

While the production of food, fiber, fuel, and timber is internalized through international markets, most environmental and welfare distributional impacts are not. Because markets for most environmental goods and services do not exist, private land use decisions are socially inefficient. To include external environmental costs in land use planning, political interference is required. However, land use policies without scientific guidance are dangerous. The scarcity of land and other resources and the complexity of interactions between land use and environment may turn today's solution into tomorrow's problem (Cowie et al. 2007). EUFASOM has been developed as an integrated scientific tool for the comprehensive economic and environmental analysis of land use and land use change.

To place EUFASOM in perspective, let us briefly review previously developed and applied tools. Existing economic land use assessment models can be distinguished a) regarding the flow of information in top-down and bottom-up systems, b) regarding the dominating analysis technique in engineering, econometric, and optimization approaches, c) regarding the system dynamics in static, recursive dynamic, and fully dynamic designs,

d) regarding the spatial scope in farm level, regional, national, multi-national, and global representations, and e) regarding the sectoral scope in agricultural, forestry, multi-sector, full economy, and coupled economic and environmental models. Additional differences involve various modeling assumptions about functional relationships (demand, supply, factor and commodity substitution) and the applied resolution over space, time, technologies, commodities, resources, and environmental impacts with the associated data. For a more detailed survey over specific land use models we refer to Lambin et al. (2000), Heistermann et al. (2006) and van der Werf and Peterson (2007).

The variation in methods indicates that land use is a complex system, whose interdependencies cannot be appropriately captured by a single approach. Instead, different methods are applied to address different questions. Using the above described classifications, EUFASOM could be characterized as a bottom-up, optimization, fully dynamic, multi-national, agricultural and forest sector model. In addition, the model portrays detailed environmental relationships and global agricultural and forestry commodity trade.

Why build another land use model? Three major arguments can be made. First, EUFASOM and its US counterpart (Alig et al. 1998) are currently the only bottom-up models, which portray the competition between agriculture, forestry, bioenergy, and nature reserves for scarce land at large scales. These models integrate observed variation in land qualities and technologies with environmental impacts and global market feedbacks. This approach enables the quantification of economic potentials for environmental problem mitigation but also the estimation of leakage effects. Leakage of environmental impacts is perhaps the biggest threat to land use policies, yet it is typically ignored in bottom-up models. Second, EUFASOM goes beyond the majority of existing economic models in portraying the environmental effects of land use. Multiple greenhouse gas and soil state impacts are estimated with detailed environmental process models. The complex dynamic relationship between land management trajectories and soil quality is represented through Markov chains (Schneider 2007). A parallel to EUFASOM developed European wetland optimization model (Jantke and Schneider 2007) estimates the impacts of land use impacts on conservation of 69 wetland species. Thus, EUFASOM is better equipped than previous models to assess impacts and interdependencies of climate, biodiversity, soil, and food policies.

Thirdly, although searches through the scientific literature may reveal numerous integrated land use assessments, the number of maintained state-of-the-art models is small. Essentially, many land use models are dissertation products where the requirement of independent work limits the quality of data and model. EUFASOM is part of an integrated assessment framework where a large team of collaborating researchers from different countries and different disciplines synthesize data, models, and expertise. The model is available for other researchers provided that improvements are shared.

Data

Bottom-up models are generally data intensive both with respect to inputs and outputs. Input data for EUFASOM describe important properties of resources, production technologies, and agricultural and forestry markets. Generally, while resource data are mainly derived from observations, economic data are computed based on producer surveys or engineering methods, environmental impacts based of land management from simulations with biophysical process models, and market data from national and international statistics. The following descriptions of EUFASOM input data can only give a brief overview. Detailed information on specific data item are available from the authors.

Most raw data are not directly used in EUFASOM but undergo transformations involving model processing, aggregation, and calibration. Detailed meteorological, nitrogen deposition, and soil data over more than 1,000 homogeneous response units (HRU) within the European Union (Balkovič 2007) are used as inputs to the EPIC model. For each HRU and all land use and land management alternatives, the EPIC model simulates in daily time steps biomass growth and multiple environmental impacts concerning greenhouse gas emissions, soil organic carbon, erosion, and nutrient leaching. However, only biomass yields and environmental impacts are passed to EUFASOM. As a result, climate and soil data are only implicitly contained in EUFASOM.

Resource data in EUFASOM include region and time period specific endowments for land quality classes, existing forests, labor, and water. National soil type distributions are estimated from a European Soil Database as described in Balkovič 2007. Existing and suitable areas for five wetland types are estimated through a GIS based spatial analysis (Schleupner 2007).

Economic data for basic agricultural management technologies are derived from the European Farm Accountancy Data Network surveys (European Commission 2008). Bioenergy data for production and processing of bioenergy are taken from results of the European Non-Food Agriculture consortium (ENFA 2008). Agricultural management costs, for which data do not exist, are estimated based on engineering equations (Hallam et al. 1999). Forest stand data are estimated with the OSKAR model based on sub-country level inventories of forest stocks, tree species and age classes covering most of Europe.

The OSKAR model employs globally applicable biophysical principles, species characteristics, and expected climate change effects predicted by the LPJ global ecosystem model (Sitch et al. 2003) to estimate forest biomass, carbon storage, forestry production and forest management costs. Forest industry inputs are based on Pöyry consulting expert estimates. Forest products life time data are based on Eggers (2002).

Current production, consumption, trade, and price data for agricultural and forest commodities are taken from EUROSTAT and FAOSTAT. Assumptions about population and gross domestic product developments and technical progress are taken from GTAP.

Model structure

This section documents the principal mathematical structure of EUFASOM, which is relatively unaffected by data updates or model expansion towards greater detail. EUFASOM is designed to emulate the full impacts of European land use on agricultural and forest markets and on environmental qualities related to land use. The model contains several key components: natural and human resource endowments, agricultural and forest production factor markets, primary and processed commodity markets, agricultural and forest technologies, and agricultural policies. Because of data requirements and computational restrictions, sector models cannot provide the same level of detail as do farm level or regional models. Rather than trying to depict millions of individual farms, EUFASOM represents typical crop, livestock, forest, and bioenergy enterprises for 23 EU member states. Possible producer adaptation is integrated through a large set of alternative land management technologies (Table 1). These technologies are described through Leontief production possibilities each of it specifying fixed quantities of multiple inputs and multiple outputs. International markets and trade relationships are currently portrayed through eleven international regions.

EUFASOM is a large mathematical program. The objective function maximizes total agricultural economic surplus subject to a set of constraining equations, which define a convex feasible region for all endogenous land use decision variables. Full model activations contains more than 6 Million individual variables and more than 1 Million individual equations. Equations and variables are condensed into indexed blocks (see Table 2). Solving EUFASOM involves the task of finding the optimal levels for all endogenous variables, i.e. those levels which maximize the economic surplus subject to compliance with all constraining equations. Economic surplus is computed as the sum across time, space, commodities, and resources of total consumers' surplus, producers' or resource owners' surplus, and governmental net payments to the agricultural sector minus the total cost of production, transportation, and processing. Basic economic theory demonstrates that maximization of the sum of consumers' plus producers' surplus yields the competitive market equilibrium. Thus, the optimal variable levels can be interpreted as equilibrium levels for land use activities under given economic, political, and technological conditions. The shadow prices on resource and commodity balance equations give market clearing prices.

To facilitate understanding of the EUFASOM structure, we will first describe the set of constraining equations and subsequently explain the objective function. Variables are denoted by capital letters. Constraint coefficients and right hand side values are represented by small italic letters. Indices of equations, variables, variable coefficients, and right hand sides are denoted by subscripts. The constraining equations depict resource and technological restrictions, intertemporal relationships, and environmental interactions.

Resource and technological restrictions

Supply and demand balance equations link agricultural and forest activities to commodity markets (Equation 1) and to factor markets and resource endowments (Equation 2). Specifically, for each region, period, and product, the total amount allocated to domestic consumption (DEMD), processing (PROC), and exports (TRAD[1]) cannot exceed the total supply through crop production (CROP), bioenergy plantations (BIOM), timber harvesting (HARV), production from standing forests (TREE), nature reserves (ECOL), livestock raising (LIVE), or imports (TRAD). Note that the explicit supply variable SUPP depicts special animal feeds and agricultural commodities in non-EU regions, for which technological data are not available.

The technical coefficients $\alpha^{CROP}_{r,t,i,j,c,u,q,m,p,y}$, $\alpha^{PAST}_{r,t,i,j,s,u,q,m,p,y}$, $\alpha^{BIOM}_{r,t,i,j,b,u,q,m,p,y}$, $\alpha^{HARV}_{r,t,i,j,f,u,a,m,p,y}$, $\alpha^{TREE}_{r,t,i,j,f,u,a,m,p,y}$, $\alpha^{ECOL}_{r,t,i,j,s,u,x,m,p,y}$, $\alpha^{LIVE}_{r,t,l,u,m,p,y}$, $\alpha^{FEED}_{r,t,l,m,y}$, and $\alpha^{PROC}_{r,t,m,y}$ indicate input requirements (negative values) of output yields (positive values). The structure of Equation 1 allows for an efficient representation of multi-input and multi-output production and for multi level processing, where outputs of the first process become inputs to the next process. Supply and demand relationships for agricultural production factors are shown in Equation 2. Particularly, the total use of each production factor or resource over all agricultural and forest activities cannot exceed the total supply of these factors (RESR) in each region and period.

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[1] The first index of the TRAD variables denotes the exporting region or country, the second denotes the importing region or country.

$$\begin{pmatrix} +\sum_{m}\left(\alpha^{PROC}_{r,t,m,y}\cdot PROC_{r,t,m}\right) \\ +\sum_{m}\left(\alpha^{FEED}_{r,t,l,m,y}\cdot FEED_{r,t,l,m}\right) \\ +\sum_{\tilde{r}} TRAD_{r,\tilde{r},t,y} \\ +DEMD_{r,t,y} \end{pmatrix} \le \begin{pmatrix} +\sum_{j,v,c,u,q,m,p}\left(\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,y}\cdot CROP_{r,t,j,v,c,u,q,m,p}\right) \\ +\sum_{j,v,s,u,q,m,p}\left(\alpha^{PAST}_{r,t,j,v,s,u,q,m,p,y}\cdot PAST_{r,t,j,v,s,u,q,m,p}\right) \\ +\sum_{j,v,b,u,q,m,p}\left(\alpha^{BIOM}_{r,t,j,v,b,u,q,m,p,y}\cdot BIOM_{r,t,j,v,b,u,q,m,p}\right) \\ +\sum_{j,v,f,u,a,m,p}\left(\alpha^{HARV}_{r,t,j,v,f,u,a,m,p,y}\cdot HARV_{r,t,j,v,f,u,a,m,p}\right) \\ +\sum_{j,v,f,u,a,m,p}\left(\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,y}\cdot TREE_{r,t,j,v,f,u,a,m,p}\right) \\ +\sum_{j,v,s,u,x,m,p}\left(\alpha^{ECOL}_{r,t,j,v,s,u,x,m,p,y}\cdot ECOL_{r,t,j,v,s,u,x,m,p}\right) \\ +\sum_{l,u,m,p}\left(\alpha^{LIVE}_{r,t,l,u,m,p,y}\cdot LIVE_{r,t,l,u,m,p}\right) \\ +\sum_{\tilde{r}} TRAD_{\tilde{r},r,t,y} \\ +SUPP_{r,t,y} \end{pmatrix}$$

Equation 1 Commodity balance (∀ t, r, and y)

Livestock farmers have a choice between different animal diets. These diets are depicted by the variable FEED and contain unprocessed crops, processed concentrates, and special feed additives. Depending on animal type and performance, diets have to meet certain nutritional targets. These nutritional restriction are integrated in EUFASOM as shown in Equation 3. Several things should be noted. First, restrictions are only active if the nutritional coefficients $\alpha^{LIVE}_{r,t,l,u,m,p,n}$ are non-zero. Second, the nutritional coefficients for feeds differ between animals types.

Livestock raising produces different types of animal manure. Manure can be returned as organic fertilizer to fields or digested to generate energy. EUFASOM restricts the total usage of manure from animal houses as fertilizer or energy source to be equal or less than the total amount of manure produced through all livestock operations. Note that the impact of manure from grazing animals is not part of this balance but is included in Equation 9.

$$\left(\begin{array}{l}
+\sum_{j,v,c,u,q,m,p}\left(\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,i}\cdot CROP_{r,t,j,v,c,u,q,m,p}\right)\\
+\sum_{j,v,s,u,q,m,p}\left(\alpha^{PAST}_{r,t,j,v,s,u,q,m,p,i}\cdot PAST_{r,t,j,v,s,u,q,m,p}\right)\\
+\sum_{j,v,b,u,q,m,p}\left(\alpha^{BIOM}_{r,t,j,v,b,u,q,m,p,i}\cdot BIOM_{r,t,j,v,b,u,q,m,p}\right)\\
+\sum_{j,v,f,u,a,m,p}\left(\alpha^{HARV}_{r,t,j,v,f,u,a,m,p,i}\cdot HARV_{r,t,j,v,f,u,a,m,p}\right)\\
+\sum_{j,v,f,u,a,m,p}\left(\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,i}\cdot TREE_{r,t,j,v,f,u,a,m,p}\right)\\
+\sum_{j,v,s,u,x,m,p}\left(\alpha^{ECOL}_{r,t,j,v,s,u,x,m,p,i}\cdot ECOL_{r,t,j,v,s,u,x,m,p}\right)\\
+\sum_{l,u,m,p}\left(\alpha^{LIVE}_{r,t,l,u,m,p,i}\cdot LIVE_{r,t,l,u,m,p}\right)\\
+\sum_{m}\left(\alpha^{PROC}_{r,t,m,i}\cdot PROC_{r,t,m}\right)\\
+\sum_{m}\left(\alpha^{FEED}_{r,t,l,m,i}\cdot FEED_{r,t,l,m}\right)
\end{array}\right)\le RESR_{r,t,i}$$

Equation 2 Resource balance (∀ r, t, and i)

$$\begin{aligned}
\sum_{l,m}\left(\alpha^{FEED}_{r,t,l,m,n^{max}}\cdot FEED_{r,t,l,m}\right) &\le \sum_{l,u,m,p}\left(\alpha^{LIVE}_{r,t,l,u,m,p,n^{max}}\cdot LIVE_{r,t,l,u,m,p}\right)\\
\sum_{l,m}\left(\alpha^{FEED}_{r,t,l,m,n^{min}}\cdot FEED_{r,t,l,m}\right) &\ge \sum_{l,u,m,p}\left(\alpha^{LIVE}_{r,t,l,u,m,p,n^{min}}\cdot LIVE_{r,t,l,u,m,p}\right)
\end{aligned}$$

Equation 3 Animal feeding restrictions (∀ r, t, and n^{min}/n^{max})

$$\begin{pmatrix} +\sum_{j,v,c,u,q,m,p}\left(\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,i}\cdot CROP_{r,t,j,v,c,u,q,m,p}\right) \\ +\sum_{m}\left(\alpha^{PROC}_{r,t,m,i}\cdot PROC_{r,t,m}\right) \end{pmatrix} \le \sum_{l,u,m,p}\left(\alpha^{LIVE}_{r,t,l,u,m,p,i}\cdot LIVE_{r,t,l,u,m,p}\right)$$

Equation 4 Manure balance (∀ r, t, and i)

Limits to agricultural production arise not only from technologies but also from the use of scarce and immobile resources. Particularly, the use of agricultural land, labor, irrigation water, and grazing units is either physically limited by regional endowments or economically limited by upward sloping supply curves for these private or public resources. In EUFASOM, all production, processing, and nature reserve variables (CROP, LIVE, BIOM, ECOL, TREE, HARV, FEED, and PROC) have associated with them resource use coefficients ($\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,i}$, $\alpha^{BIOM}_{r,t,j,v,b,u,q,m,p,i}$, $\alpha^{ECOL}_{r,t,j,v,s,u,x,m,p,i}$, $\alpha^{LIVE}_{r,t,l,u,m,p,i}$, $\alpha^{HARV}_{r,t,j,v,f,u,a,m,p,i}$, $\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,i}$, $\alpha^{FEED}_{r,t,l,m,i}$, $\alpha^{PROC}_{r,t,m,i}$), which resource requirements per unit of production. The mathematical representation of physical resource constraints in EUFASOM is straightforward and displayed in Equation 5. These equations simply force the total use of natural or human resources to be at or below given regional endowments $\beta_{r,t,i}$. Economic resource constraints are part of the objective function.

$$RESR_{r,t,i} \le \beta_{r,t,i}$$

Equation 5 Resource limitations (∀ r, t, and i)

Intertemporal restrictions

Intertemporal restrictions form an important part of EUFASOM and include initial conditions, forest and soil state transition equations, and land use change restrictions. Terminal values for forests are included in the objective function section. Initial conditions link activities in the first model period (INIT) to observed values (Equation 6). These conditions can be placed at a detailed or aggregated level. For example, while forest activities in EUFASOM include three alternative thinning regimes, observed forest inventories are only available by region, age cohort, and species. Thus, Equation 6 enforces these aggregated identities but let the model choose the optimal distribution of thinning regimes in the first period. Similarly, the distribution of existing and potential wetlands can be enforced for individual wetland types and size classes or for aggregates.

$$\mathrm{INIT}_{r,j,v,s,u,q,m,p} = \phi_{r,j,v,s,u,q,m,p}$$

Equation 6 Initial land allocation (∀ r, t, v, s, u, q, m, and p)

In each region and for each period, EUFASOM explicitly distinguishes standing forests by species composition, age cohort, ownership, management, and soil characteristics. Age cohorts and time periods are both resolved to 5-year intervals. The distribution of forest types in a certain period is constrained by planting and harvesting activities in previous time periods (Equation 7). Particularly, the area of standing and harvested forests above the first age cohort cannot exceed the area of the same forest type one period earlier and one age class lower. However, if a forest has reached the last age cohort, it will remain in this cohort in the next period as well.

$$\begin{pmatrix} +\mathrm{TREE}_{r,t,j,v,f,u,a,m,p}\Big|_{a>1} \\ +\mathrm{HARV}_{r,t,j,v,f,u,a,m,p}\Big|_{a>1} \end{pmatrix} \leq \begin{pmatrix} +\mathrm{TREE}_{r,t-1,j,v,f,u,a-1,m,p}\Big|_{t>1 \wedge a>1} \\ +\mathrm{TREE}_{r,t-1,j,v,f,u,a,m,p}\Big|_{t>1 \wedge a=A} \\ +\mathrm{INIT}_{r,j,v,f,u,a,m,p}\Big|_{t=1} \end{pmatrix}$$

Equation 7 Forest transition (∀ r, t, j, v, f, u, a, m, and p)

While new forest plantations are not affected by Equation 7, EUFASOM limits the possible species change via reforestation (Equation 8). Particularly, only if the parameter $\vartheta_{r,f,\tilde{f}}$ has a value of 1, then species $\tilde{f}$ can be fully planted on all previously harvested areas of species f. For values less than 1, allowed reforestation of $\tilde{f}$ on harvested areas of f is accordingly reduced. No restriction is currently placed on afforestation, i.e. if agricultural land is converted to forest, all possible species for this region can be planted.

$$\begin{pmatrix} +\sum_{v,\tilde{f},m,p} \vartheta_{r,f,\tilde{f}} \cdot \mathrm{TREE}_{r,t,j,v,\tilde{f},u,a,m,p} \\ +\mathrm{LUCH}_{r,t,j,f,u,-} \end{pmatrix}\Bigg|_{a=1} \leq \begin{pmatrix} +\sum_{\tilde{t},v,m,p} \mathrm{HARV}_{r,\tilde{t},j,v,f,u,a,m,p} \\ +\mathrm{LUCH}_{r,t,j,f,u,+} \end{pmatrix}\Bigg|_{\tilde{t}\leq t}$$

Equation 8 Reforestation (∀ r, t, j, and f)

The land management path over time influences crop yields and emissions. While reduced tillage may sequester soil organic carbon on previously deep-tilled soils, positive net emissions may occur if reduced tillage is employed after several decades of zero tillage. The complex relationship between management dynamics and soil fertility is approximated in EUFASOM by a Markov Process (Equation 9). Different soil states are represented by the index v. The soil state transition probability matrices $\rho_{r,j,\tilde{v},s,u,x,m,p,v}$ for crops, biomass plantations, forests, and ecological reserves contain the probabilities of moving from soil state $\tilde{v}$ to soil state v after one time period. These matrices are exogenously derived from EPIC model simulations (Schmid et al. 2007). Transition probabilities differ across regions, soil textures, planted species, and management alternatives. A more detailed technical explanation and application to the effects different tillage methods is contained in Schneider (2007).

$$\begin{pmatrix} +\sum_{c,u,q,m,p} CROP_{r,t,j,v,c,u,q,m,p} \\ +\sum_{s,u,q,m,p} PAST_{r,t,j,v,s,u,q,m,p} \\ +\sum_{b,u,q,m,p} BIOM_{r,t,j,v,b,u,q,m,p} \\ +\sum_{f,u,a,m,p} TREE_{r,t,j,v,f,u,a,m,p} \\ +\sum_{s,u,x,m,p} ECOL_{r,t,j,v,s,u,x,m,p} \end{pmatrix} \le \begin{pmatrix} +\sum_{\tilde{v},c,u,q,m,p} \left(\rho^{CROP}_{r,j,\tilde{v},c,u,q,m,p,v} \cdot CROP_{r,t-1,j,\tilde{v},c,u,q,m,p}\right) \\ +\sum_{\tilde{v},s,u,q,m,p} \left(\rho^{PAST}_{r,j,\tilde{v},s,u,q,m,p,v} \cdot PAST_{r,t-1,j,\tilde{v},s,u,q,m,p}\right) \\ +\sum_{\tilde{v},b,u,q,m,p} \left(\rho^{BIOM}_{r,j,\tilde{v},b,u,q,m,p,v} \cdot BIOM_{r,t-1,j,\tilde{v},b,u,q,m,p}\right) \\ +\sum_{\tilde{v},f,u,a,m,p} \left(\rho^{TREE}_{r,j,\tilde{v},f,u,a,m,p,v} \cdot TREE_{r,t-1,j,\tilde{v},f,u,a,m,p}\right) \\ +\sum_{\tilde{v},s,u,x,m,p} \left(\rho^{ECOL}_{r,j,\tilde{v},s,u,x,m,p,v} \cdot ECOL_{r,t-1,j,\tilde{v},s,u,x,m,p}\right) \end{pmatrix}$$

Equation 9 Soil state transition (∀ r, t, j, and v)

Dynamic changes in the agricultural and forest sector include changes in land allocation between forests, crop production, bioenergy plantations, and nature reserves. For each period, EUFASOM traces these land use changes (LUCH) explicitly, both with respect to the preceding period (Equation 10) and with respect to the initial allocation (Equation 11). Changes to the preceding periods are penalized with adjustment costs in the objective function. Land use changes with respect to the initial situation are restricted to maximum transfer $\eta_{r,t,j,s,u,\{+,-\}}$. These upper bounds on land use changes are determined by geographical analyses regarding suitability. Suitability criteria for wetland restoration are described in Schleupner (2007). If $\eta_{r,t,j,s,u,\{+,-\}}$ equals zero, then Equation 11 is not enforced.

$$
\mathrm{LUCH}_{r,t,j,s,u,\{+,-\}} = \psi_{\{+,-\}} \cdot \left(\begin{array}{l}
+ \sum\limits_{v,q,m,p} \left(\mathrm{CROP}_{r,t,j,v,s,u,q,m,p} - \mathrm{CROP}_{r,t-1,j,v,s,u,q,m,p} \Big|_{t>1} \right) \\
+ \sum\limits_{v,q,m,p} \left(\mathrm{PAST}_{r,t,j,v,s,u,q,m,p} - \mathrm{PAST}_{r,t-1,j,v,s,u,q,m,p} \Big|_{t>1} \right) \\
+ \sum\limits_{v,q,m,p} \left(\mathrm{BIOM}_{r,t,j,v,s,u,q,m,p} - \mathrm{BIOM}_{r,t-1,j,v,s,u,q,m,p} \Big|_{t>1} \right) \\
+ \sum\limits_{v,a,m,p} \left(\mathrm{TREE}_{r,t,j,v,s,u,a,m,p} - \mathrm{TREE}_{r,t-1,j,v,s,u,a,m,p} \Big|_{t>1} \right) \\
+ \sum\limits_{v,x,m,p} \left(\mathrm{ECOL}_{r,t,j,v,s,u,x,m,p} - \mathrm{ECOL}_{r,t-1,j,v,s,u,x,m,p} \Big|_{t>1} \right) \\
- \sum\limits_{v,q,m,p} \phi_{r,j,v,s,u,q,m,p} \Big|_{t=1}
\end{array} \right)
$$

Equation 10 Land use change ($\forall$ r, t, j, s, u, and $\{+,-\}$)

$$
\mathrm{LUCH}_{r,t,j,s,u,\{+,-\}} \le \eta_{r,t,j,s,u,\{+,-\}} \Big|_{\eta_{r,t,j,s,u,\{+,-\}} \ge 0}
$$

Equation 11 Land use change limits ($\forall$ r, t, j, s, and u)

Environmental Interactions

The quantification of interactions between regulated and unregulated environmental qualities and agricultural, forest, and nature conservation activities is a major component for integrated land use analyses. The basic EUFASOM contains accounting equations a) for environmental fluxes (Equation 12), i.e. greenhouse gas, nutrient, and soil emissions, and b) for environmentally important stocks (Equation 13) other than resources accounted in Equation 2. These stocks include dead wood pools in forests but also wood product pools both of which impact greenhouse gas balances. The mathematical formulation of Equation 12 is a simple summation of activity levels multiplied by impact coefficients over species, soil qualities, management, sites, and policies. The environmental impact coefficients, i.e. $\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,e}$, $\alpha^{BIOM}_{r,t,j,v,b,u,q,m,p,e}$, $\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,e}$, $\alpha^{ECOL}_{r,t,j,v,s,u,x,m,p,e}$, $\alpha^{PROC}_{r,t,m,e}$, and $\alpha^{FEED}_{r,t,l,m,e}$, form one part of the link from biochemophysical process models to EUFASOM.

$$\mathrm{EMIT}_{r,t,e} = \left(\begin{array}{l} + \sum\limits_{j,v,c,u,q,m,p} \left(\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,e} \cdot \mathrm{CROP}_{r,t,j,v,c,u,q,m,p} \right) \\ + \sum\limits_{j,v,c,u,q,m,p} \left(\alpha^{PAST}_{r,t,j,v,c,u,q,m,p,e} \cdot \mathrm{PAST}_{r,t,j,v,c,u,q,m,p} \right) \\ + \sum\limits_{j,v,b,u,q,m,p} \left(\alpha^{BIOM}_{r,t,j,v,b,u,q,m,p,e} \cdot \mathrm{BIOM}_{r,t,j,v,b,u,q,m,p} \right) \\ + \sum\limits_{j,v,f,u,a,m,p} \left(\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,e} \cdot \mathrm{TREE}_{r,t,j,v,f,u,a,m,p} \right) \\ + \sum\limits_{j,v,s,u,x,m,p} \left(\alpha^{ECOL}_{r,t,j,v,s,u,x,m,p,e} \cdot \mathrm{ECOL}_{r,t,j,v,s,u,x,m,p} \right) \\ + \sum\limits_{s,u,m,p} \left(\alpha^{LIVE}_{r,t,s,u,m,p,e} \cdot \mathrm{LIVE}_{r,t,s,u,m,p} \right) \\ + \sum\limits_{s,u,\{+,-\}} \left(\alpha^{LUCH}_{r,t,s,u,\{+,-\},e} \cdot \mathrm{LUCH}_{r,t,s,u,\{+,-\}} \right) \\ + \sum\limits_{m} \left(\alpha^{PROC}_{r,t,m,e} \cdot \mathrm{PROC}_{r,t,m} \right) \\ + \sum\limits_{m,l} \left(\alpha^{FEED}_{r,t,l,m,e} \cdot \mathrm{FEED}_{r,t,l,m} \right) \\ + \mathrm{STCK}_{r,t,e} - \mathrm{STCK}_{r,t-1,e} \end{array} \right)$$

Equation 12 Emission accounting equation (∀ r, t, and e)

$$\mathrm{STCK}_{r,t,d} = \left(\begin{array}{l} + \partial_{r,t-1,d} \cdot \mathrm{STCK}_{r,t-1,d} \\ + \sum\limits_{j,v,f,u,a,m,p} \left(\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,d} \cdot \mathrm{TREE}_{r,t,j,v,f,u,a,m,p} \right) \\ + \sum\limits_{j,v,f,u,a,m,p} \left(\alpha^{HARV}_{r,t,j,v,f,u,a,m,p,d} \cdot \mathrm{HARV}_{r,t,j,v,f,u,a,m,p} \right) \\ + \sum\limits_{f,u} \left(\alpha^{LUCH}_{r,t,f,u,-,d} \cdot \mathrm{LUCH}_{r,t,f,u,-} \right) \end{array} \right)$$

Equation 13 Dead wood and commodity stock equation (∀ r, t, and d)

Equation 13 computes the current stock levels as sum of discounted previous stocks plus stock additions from current activities. Stock discounts are derived from dead wood decomposition and product lifetime functions (Eggers 2002).

All environmental qualities (EMIT, STCK, RESR) can be subjected to minimum or maximum restrictions[1]. In addition, objective function coefficients on emission or technology variables allow the representation of environmental taxes and subsidies. Note that the basic model setup establishes only a one-directional link from environmental impact models to EUFASOM. Environmental feedbacks can be included via iterative links. Similarly, inconsistencies between aggregated and geographically downscaled EUFASOM results could be decreased through iterative procedures.

Objective Function

EUFASOM simulates detailed land use adaptations, market and trade equilibrium changes, and environmental consequences for political, technical, and environmental scenarios related to agriculture, forestry, and nature. The objective function incorporates all major drivers for these changes, i.e. cost coefficients for land use and commodity processing alternatives, adjustment costs for major land use changes, market price changes for commodities and production factors, trade costs, political incentives and disincentives, and terminal values for standing forests. Mathematically, EUFASOM maximizes consumer surplus in final commodity markets plus producer or resource owner surplus in all price-endogenous factor markets minus technological, trade, adjustment, and policy related costs plus subsidies and terminal values. Future costs and benefits are discounted by an exogenously specified rate.

---

[1] The corresponding equations are trivial and therefore omitted.

$$
\text{Maximize WELF} = \sum_{t} \left(\partial_t \cdot \left(\begin{array}{l}
\sum_{r,y} \left[\int_{y} \varphi_{r,t,y}^{DEMD} \left(\text{DEMD}_{r,t,y} \right) d(\cdot) \right] \\
- \sum_{r,y} \left[\int_{n} \varphi_{r,t,y}^{SUPP} \left(\text{SUPP}_{r,t,y} \right) d(\cdot) \right] \\
- \sum_{r,i} \left[\int_{n} \varphi_{r,t,i}^{RESR} \left(\text{RESR}_{r,t,i} \right) d(\cdot) \right] \\
- \sum_{r,j,v,c,u,q,m,p} \left(\tau_{r,t,j,v,c,u,q,m,p}^{CROP} \cdot \text{CROP}_{r,t,j,v,c,u,q,m,p} \right) \\
- \sum_{r,j,v,s,u,q,m,p} \left(\tau_{r,t,j,v,s,u,q,m,p}^{PAST} \cdot \text{PAST}_{r,t,j,v,s,u,q,m,p} \right) \\
- \sum_{r,j,v,b,u,q,m,p} \left(\tau_{r,t,j,v,b,u,q,m,p}^{BIOM} \cdot \text{BIOM}_{r,t,j,v,b,u,q,m,p} \right) \\
- \sum_{r,j,v,f,u,a,m,p} \left(\tau_{r,t,j,v,f,u,a,m,p}^{HARV} \cdot \text{HARV}_{r,t,j,v,f,u,a,m,p} \right) \\
- \sum_{r,j,v,f,u,a,m,p} \left(\tau_{r,t,j,v,f,u,a,m,p}^{TREE} \cdot \text{TREE}_{r,t,j,v,f,u,a,m,p} \right) \\
- \sum_{r,j,v,s,u,x,m,p} \left(\tau_{r,t,j,v,s,u,x,m,p}^{ECOL} \cdot \text{ECOL}_{r,t,j,v,s,u,x,m,p} \right) \\
- \sum_{r,l,u,m,p} \left(\tau_{r,t,l,u,m,p}^{LIVE} \cdot \text{LIVE}_{r,t,l,u,m,p} \right) \\
- \sum_{r,m} \left(\tau_{r,t,m}^{PROC} \cdot \text{PROC}_{r,t,m} \right) \\
- \sum_{r,l,m} \left(\tau_{r,t,l,m}^{FEED} \cdot \text{FEED}_{r,t,l,m} \right) \\
- \sum_{r,j,u,\{+,-\}} \left(\tau_{r,t,j,s,u,\{+,-\}}^{LUCH} \cdot \text{LUCH}_{r,t,j,s,u,\{+,-\}} \right) \\
- \sum_{r,\tilde{r},y} \left(\tau_{r,\tilde{r},t,y}^{TRADE} \cdot \text{TRAD}_{r,\tilde{r},t,y} \right) \\
- \sum_{r,e} \left(\tau_{r,t,e}^{EMIT} \cdot \text{EMIT}_{r,t,e} \right)
\end{array} \right) \right)
+ \sum_{r,j,v,f,u,a,m,p} \left(\nu_{r,j,v,f,u,a,m,p}^{TREE} \cdot \text{TREE}_{r,T,j,v,f,u,a,m,p} \right)
$$

Equation 14 Economic surplus maximizing objective function

The technical realization of EUFASOM's objective function is displayed in Equation 14[1]. Note that consumers' and producers' surplus is not directly calculated. Instead, EUFASOM computes the difference between the areas underneath all demand curves minus the areas underneath all supply curves. For competitive markets, this technique is equivalent to surplus maximization. Moreover, the theoretically nonlinear supply and demand area integrals in EUFASOM are linearly approximated. The approximation is given in the appendix. Supply and demand curves are specified as linear or constant elasticity functions. To avoid infinite integrals, constant elasticity demand functions are truncated. A truncated demand curve is horizontal between zero and a small demand quantity and downward sloping thereafter.

To place EUFASOM solutions in perspective, alternative objectives can be specified. In particular, Equation 15 allows the computation of commodity supply frontiers and technical limits on emission reductions. Alternative objectives can be activated for single or multiple regions, periods, commodities, and emission accounts by assigning a value of one to exogenous control parameters ($\theta^{DEMD}_{r,t,y}$, $\theta^{ECOL}_{r,t,j,v,s,u,x,m,p}$, $\theta^{EMIT}_{r,t,e}$). If the sum over all control parameters is non-zero, EUFASOM automatically deactivates the primary surplus maximizing objective and uses the alternative objective function. The use of Equation 15 provides not only model and data insight but also shows important differences between economic and technical constraints.

[1] In displaying the objective function, several modifications have been made to ease readability: a) the linearly approximated integration terms are not shown explicitly, b) artificial variables for detecting infeasibilities are omitted, and c) conditions are omitted.

$$
\text{Maximize OBJ2} = \begin{pmatrix} +\sum\limits_{r,t,y} \left(\theta^{DEMD}_{r,t,y} \cdot DEMD_{r,t,y} \right) \\ + \sum\limits_{r,t,j,v,s,u,x,m,p} \left(\theta^{ECOL}_{r,t,j,v,s,u,x,m,p} \cdot ECOL_{r,t,j,v,s,u,x,m,p} \right) \\ -\sum\limits_{r,t,e} \left(\theta^{EMIT}_{r,t,e} \cdot EMIT_{r,t,e} \right) \end{pmatrix}
$$

Equation 15   Alternative objective function

European Bioenergy and Wetland Targets – An EUFASOM Illustration

The main purpose of this study is to document the mathematical structure of EUFASOM. However, in this section we will briefly illustrate the use of the model through a small scenario experiment. Bioenergy production and wetland preservation constitute two major political objectives of the European government. While the first goal includes managed dedicated energy crop plantations, the second one usually requires the establishment of rather undisturbed nature reserves. Moreover, both options are mutually exclusive with food production. This raises an important questions for policymakers: how does the competition between food, bioenergy plantations, and wetland reserves for scarce land affect the competitive economic potential of these environmental goals? EUFASOM is well suited to address this question. The following scenario setup is used. First, bioenergy policies are represented by biomass targets up to 300 million wet tons. This amount of biomass would roughly be required to generate about 20% of the current total electricity consumption in the European Union. Second, to avoid negative ecological spillovers, existing wetlands and forests are protected and cannot be used for agriculture or bioenergy plantations.

Aggregated economic potentials of wetland restoration are displayed in Figure 1. The 100% biomass target corresponds to a European wide requirement of 300 million wet tons. As shown, with such a constraint, wetland subsidies as high as 800 Euro per ha are insufficient to induce restoration. For reduced biomass targets, restoration potentials are higher. In all cases, increasing opportunity costs lead to increased marginal costs of restoration. Figure 1 also illustrates that the competition between bioenergy production and wetland restoration does not increase linearly. While the difference between no and a 25% biomass target is small, a relative large gap exists between the 25% and 50% targets.

The interaction between food production and environmental goals is shown in Figure 2. The line labeled "EU25wide" shows the wetland restoration potential for wetland subsidies established in all European countries. The second line, labeled "national" forms the sum of 23 independent assessments. In each of these national assessments, the wetland subsidy is only established in the respective nation. For both setups, a 50% biomass constraint is enforced jointly over all countries. Figure 2 shows that starting from a subsidy level of 300 Euro per ha, the two lines drift apart. The sum of national assessments gives a higher restoration potential because bioenergy and agricultural production simply shift to those countries without wetland subsidy. At the highest shown subsidy level, the sum of national assessments overestimates the economic potential by almost 10 million ha.

Conclusions

This paper describes the mathematical structure of the European Forest and Agricultural Sector Optimization Model. The model has been developed to assess the economic and environmental impacts of political, technological, and environmental change on European land use. EUFASOM goes beyond existing approaches in portraying the interdependencies between food, water, bioenergy, climate, wildlife preservation, and soils. Despite a huge amount of data, variables, and equations, the model is built on simple principles. These principles are captured through 14 fundamental equations. The large model size results from repeated implementations of these equations over space, time, commodities, technologies, and environmental qualities.

The strength of EUFASOM lies in its simultaneous representation of observed resource and technological heterogeneity, global commodity markets, and multiple environmental qualities. Land scarcity and land competition between traditional agriculture, timber production, nature reserves, livestock pastures, and bioenergy plantations is explicitly captured. Environmental change, technological progress, and policies can be investigated in parallel. Consequently, EUFASOM is well-suited to a) examine the competitive economic potential of agricultural and forestry based mitigation of environmental problems and contrast these to technical or economic potentials without market feedbacks, b) estimate leakage, i.e. how European environmental policies affect non-European land use and c) analyze synergies and trade-offs between different environmental objectives.

Finally, several limitations should be noted. First, EUFASOM is a partial equilibrium model and does not adequately account for income effects. Second, EUFASOM does not value benefits and damages from different environmental qualities but considers only exogenous values, i.e. carbon prices or ecosystem values. Third, due to data constraints, validation of EUFASOM is limited to comparisons between the base period solution and observations. Fourth, the quality of the model reflects the quality of the input data and the quality of linked models. Fifth, EUFASOM results are derived from the optimal solution of a mathematical program and as such constitute point estimates without probability distribution.

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References

Alig, R.J., D.M. Adams, and B.A. McCarl (1998). "Impacts of Incorporating Land Exchanges Between Forestry and Agriculture in Sector Models", Journal of Agricultural and Applied Economics, 30(2), 389-401,

Balkovič, J., Schmid, E., Moltchanova, E., Skalský, R., Poltárska, K., Müller, B., Bujnovský, R. (2007). "Data processing." In: Stolbovoy, V., Montanarella, L., Panagos, P.(eds.), Carbon Sink Enhancement in Soils of Europe: Data, Modeling, Verification. JRS Scientific and Technical Reports, EUR 23037 EN – Joint Research Centre – Institute for Environment and Sustainability, Luxembourg, 183 p, ISBN 978-92-79-07691-6

Briunsma, J. (2003) "World agriculture: towards 2015/2030: an FAO perspective." FAO/Earthscan, 432 pp.

Cowie, A., U.A. Schneider and L. Montanarella (2007). "Potential synergies between existing multilateral environmental agreements in the implementation of Land Use, Land Use Change and Forestry activities." Environmental Science & Policy 10(4):335-352

Eggers, T. (2002). The Impacts of Manufacturing and Utilisation of Wood Products on the European Carbon Budget. Internal Report 9, European Forest Institute, Joensuu, Finland. 90 p.

European Economic Community (1992). Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.

European Non-Food Agriculture (ENFA) Consortium (2008). URL: http://www.fnu.zmaw.de/European-Non-Food-Agriculture.5700.0.html

European Union (2003). "Directive of the European Parliament and of Council on the promotion of the use of biofuels or other renewable fuels for transport". 2003/30/EC. 08/05/2003. Brussels, Belgium.

European Commission (2008). "FADN Reference database". Agriculture Directorate General. URL: http://ec.europa.eu/agriculture/rica/reference_en.cfm.

Food and Agricultural Organization (FAO). 2007. FAOstat database. URL: http://faostat.fao.org/

Commision of the European Communities (2008). “20 20 by 2020 Europe's climate change opportunity”. Communication from the Commission to the European Parliament, the Council , the Council, the European Economic and Social Committee and the Committee of the Regions. COM(2008) 30 final. 23/01/2008. Brussels, Belgium.

Hallam, A. & Eidman, V. E. & Morehart, M. & Klonsky, K. & editors (1999). "Commodity Costs and Returns Estimation Handbook: A Report of the AAEA Task Force on Commodity Costs and Returns," Staff General Research Papers 1315, Iowa State University, Department of Economics.

Heistermann, M. & Muller, C. & Ronneberger, K. (2006). “Land in sight?: Achievements, deficits and potentials of continental to global scale land-use modeling”. Agriculture, Ecosystems & Environment. 114(2-4):141-158.

Jantke, K. & Schneider, U. (2007): Land-use option biodiversity conservation - towards the integrated assessment of agriculture, forestry and conservation in land use modelling. 21st Annual Meeting of the Society for Conservation Biology, Port Elizabeth, South Africa, July 1-5

Lambin, E. F. & Rounsevell, M. D. A. & Geist, H. J. (2000). “Are agricultural land-use models able to predict changes in land-use intensity?”. Agriculture, Ecosystems & Environment 82(1-3):321-331.

Rajagopal, D. & Zilberman, D. (2007), “Review of environmental, economic and policy aspects of biofuels”. Policy Research Working Paper 4341. The World Bank, Development Research Group, Washington, DC, USA.

Schneider, U.A. (2007). “Soil organic carbon changes in dynamic land use decision models.” Agriculture, Ecosystems and Environment. 119:359-367.

Schleupner, C. (2007). “Wetland Distribution Modeling for Optimal Land Use Options in Europe.” Working paper FNU-135, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg.

Schmid E., Balkovic J., and Skalsky R., (2007): Biophysical impact assessment of crop land management strategies in EU25 using EPIC. In: Stolbovoy V., L. Montanarella, and P. Panagos: Carbon Sink Enhancement in Soils of Europe: Data Modelling, Verification. JRC Scientific and Technical Reports. European Communities 2007, Luxembourg. 160 - 183. ISBN 978-92-79-07691-6

Smith, P., Janzen, H., Martino, D., Zucong, Z., Kumar, P., McCarl, B. A., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Genxing, P., Romanekov, V., Schneider, U. A., Towprayoon, S., Wattenbach, M., and Smith, J. (2008). “Greenhouse gas mitigation in agriculture.” Philosophical Transactions of the Royal Society 363(1492):789-813.

Sitch S, Smith B, Prentice I C, Arneth A, Bondeau A, Cramer W, Kaplan J, Levis S, Lucht W, Sykes M, Thonicke K, and Venevski S. 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ Dynamic Vegetation Model. Global Change Biology 9:161-185.

Van der Werf, E. & Peterson, S. (2007), "Modeling linkages between climate policy and land use: An overview". FEEM Working Papers 56.2007, Fondazione Eni Enrico Mattei, Milano, Italy.

Williams, J.R. (1996). "Using soil erosion models for global change studies." Journal of Soil and Water Conservation 51(5):381-385.

Table 1 Major indexes in EUFASOM

Index	Symbol[1]	Elements
Time Periods	t	2005-2010, 2010-2015, …, 2145-2150
Regions	r	25 EU member states, 11 Non-EU international regions
Species	s	All individual and aggregate species categories
Crops	c(s)	Soft wheat, hard wheat, barley, oats, rye, rice, corn, soybeans, sugar beet, potatoes, rapeseed, sunflower, cotton, flax, hemp, pulse
Trees	f(s)	Spruce, larch, douglas fir, fir, scottish pine, pinus pinaster, poplar, oak, beech, birch, maple, hornbeam, alnus, ash, chestnut, cedar, eucalyptus, ilex locust, 4 mixed forest types
Perennials	b(s)	Miscanthus, Switchgrass, Reed Canary Grass, Poplar, Willow, Arundo, Cardoon, Eucalyptus
Livestock	l(s)	Dairy, beef cattle, hogs, goats, sheep, poultry
Wildlife	w(s)	43 Birds, 9 mammals, 16 amphibians, 4 reptiles
Products	y	17 crop, 8 forest industry, 5 bioenergy, 10 livestock
Resources/Inputs	i	Soil types, hired and family labor, gasoline, diesel, electricity, natural gas, water, nutrients
Soil types	j(i)	Sand, loam, clay, bog, fen, 7 slope, 4 soil depth classes
Nutrients	n(i)	Dry matter, protein, fat, fiber, metabolizable energy, Lysine and
Technologies	m	alternative tillage, irrigation, fertilization, thinning, animal housing and manure management choices
Site quality	q	Age and suitability differences
Ecosystem state	x(q)	Existing, suitable, marginal
Age cohorts	a(q)	0-5, 5-10, …, 295-300 [years]
Soil state	v	Soil organic classes
Structures	u	FADN classifications (European Commission 2008)
Size classes	z(u)	< 4, 4 - < 8, 8 - < 16, 16 - < 40, 40- < 100, >= 100 all in ESU (European Commission 2008)
Farm specialty	o(u)	Field crops, horticulture, wine yards, permanent crops, dairy farms, grazing livestock, pigs and or poultry, mixed farms
Altitude levels	h(u)	< 300, 300 – 600, 600 – 1100, > 1100 meters
Environmental qualities	e	16 Greenhouse gas accounts, wind and water erosion, 6 nutrient emissions, 5 wetland types
Policies	p	Alternative policies

[1] Parent indexes are given in brackets

Table 2 Major variables in EUFASOM

Variable	Unit	Type	Description
CROP	1E3 ha	≥ 0	Crop production
PAST	1E3 ha	≥ 0	Pasture
LIVE	mixed	≥ 0	Livestock raising
FEED	mixed	≥ 0	Animal feeding
TREE	1E3 ha	≥ 0	Standing forests
HARV	1E3 ha	≥ 0	Forest harvesting
BIOM	1E3 ha	≥ 0	Biomass crop plantations for bioenergy
ECOL	1E3 ha	≥ 0	Wetland ecosystem reserves
LUCH	1E3 ha	≥ 0	Land use changes
RESR	mixed	≥ 0	Factor and resource usage
PROC	mixed	≥ 0	Processing activities
SUPP	1E3 t	≥ 0	Supply
DEMD	1E3 t	≥ 0	Demand
TRAD	1E3 t	≥ 0	Trade
EMIT	mixed	Free	Net emissions
STCK	mixed	≥ 0	Environmental and product stocks
WELF	1E6 €	Free	Economic Surplus

Table 3 Major parameters in EUFASOM

Symbol	Description
α	Technical coefficients (yields, requirements, emissions)
τ	Objective function coefficients
φ	Supply and demand functions
∂	Discount rate, product depreciation, dead wood decomposition
β	Resource endowments
ϑ	Soil state transition probabilities
η	Land use change limits
ϕ	Initial land allocation
ψ	Sign switch ($\psi_{+} = 1$, $\psi_{-} = -1$)
θ	Alternative objective function parameters

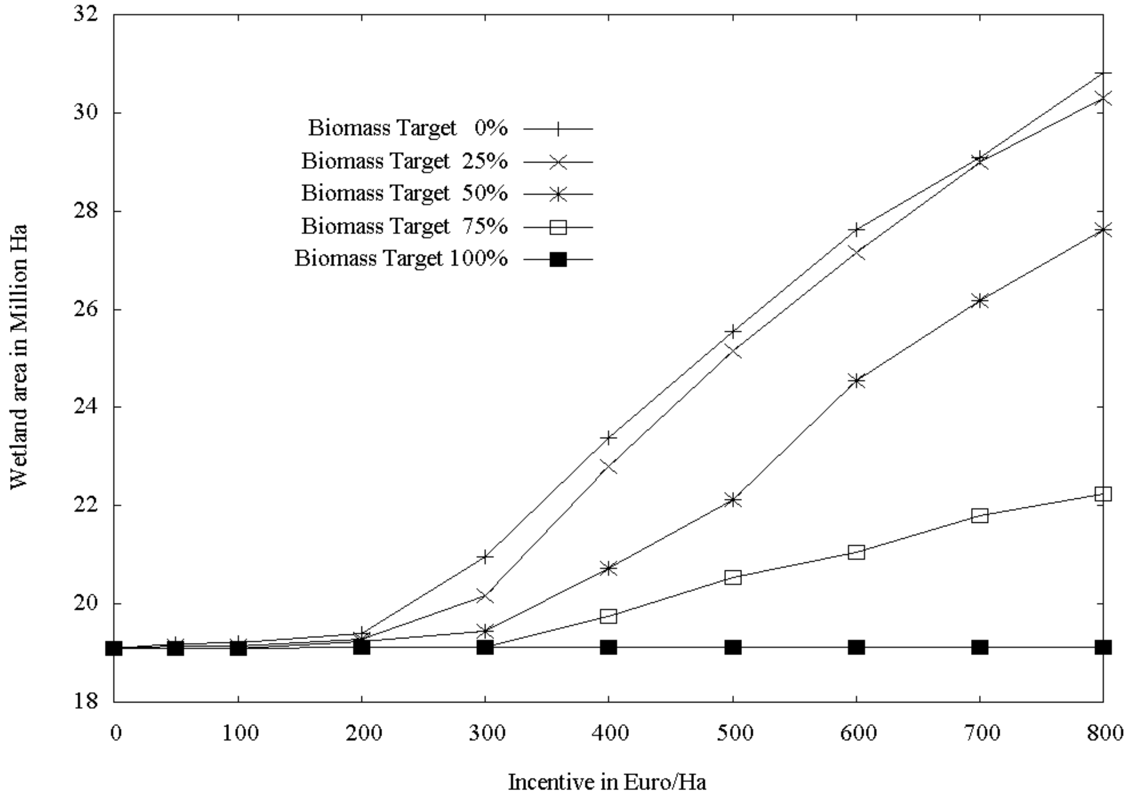

Figure 1 **Competitive economic wetland restoration potentials for different biomass targets and different wetland subsidies (horizontal axis)**

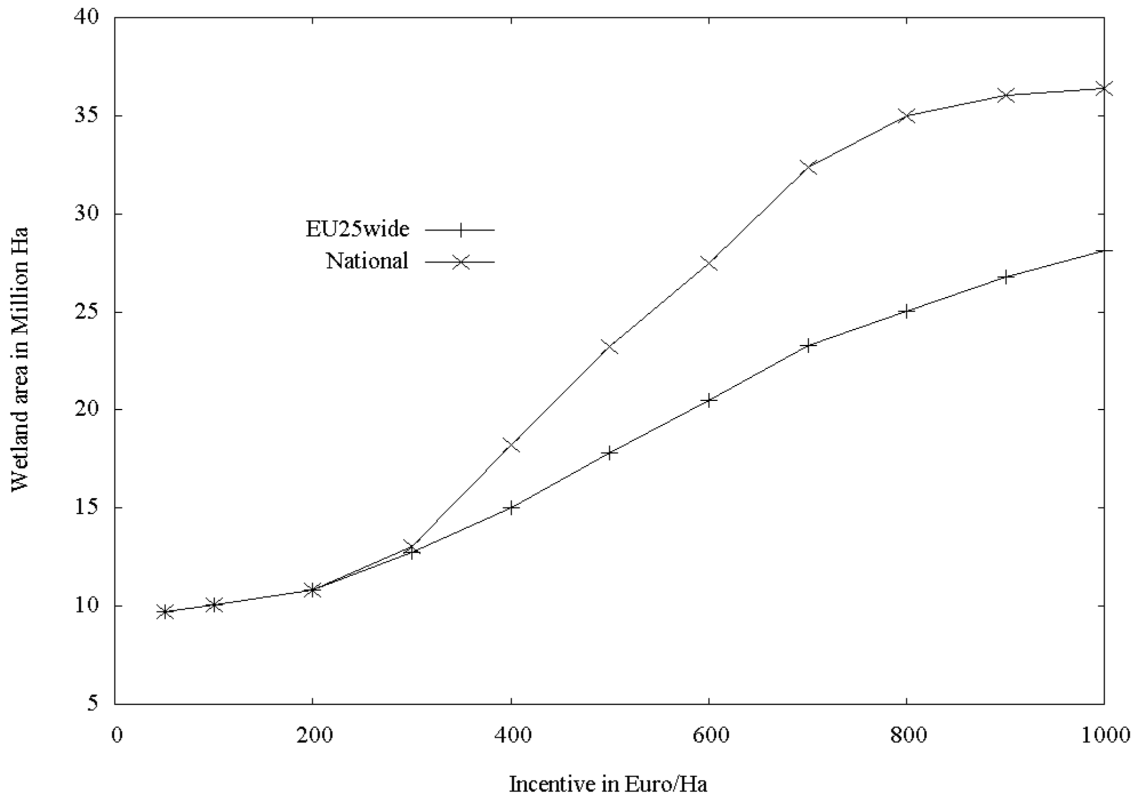

Figure 2 **Economic wetland potentials for a) simultaneous wetland subsidies in all EU countries and b) sum of independently obtained national potentials assuming that subsidy is only established in the respective country**

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Schleupner, C. (2005), *Spatial Analysis As Tool for Sensitivity Assessment of Sea Level Rise Impacts on Martinique*, **FNU-71**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. download

Sesabo, J.K. and R.S.J. Tol (2005), *Factors affecting Income Strategies among households in Tanzanian Coastal Villages: Implication for Development-Conservation Initiatives*, **FNU-70**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. download

Fisher, B.S., G. Jakeman, H.M. Pant, M. Schwoon. and R.S.J. Tol (2005), *CHIMP: A Simple Population Model for Use in Integrated Assessment of Global Environmental Change*, **FNU-69,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. download

Rehdanz, K. and R.S.J. Tol (2005), *A No Cap But Trade Proposal for Greenhouse Gas Emission Reduction Targets for Brazil, China and India*, **FNU-68,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. download

Zhou, Y. and R.S.J. Tol (2005), *Water Use in China's Domestic, Industrial and Agricultural Sectors: An Empirical Analysis*, **FNU-67**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. fileadmin/fnu-files/publication/working-papers/WD_ZhouFNU67.pdfdownload

Rehdanz, K. (2005), *Determinants of residential space heating expenditures in Germany*, **FNU-66**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. download

Ronneberger, K., R.S.J. Tol and U.A.Schneider (2005), *KLUM: A simple model of global agricultural land use as a coupling tool of economy and vegetation*, **FNU-65**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. download

Tol, R.S.J. (2005), *The Benefits of Greenhouse Gas Emission Reduction: An Application of FUND*, **FNU-64**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg.download

Röckmann, C., M.A. St.John, U.A.Schneider, F.W. Köster, F.W. and R.S.J. Tol (2006), *Testing the implications of a permanent or seasonal marine reserve on the population dynamics of Eastern Baltic cod under varying environmental conditions*, **FNU-63-revised**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. download

Letsoalo, A., J. Blignaut, T. deWet, M. de Wit, S. Hess, R.S.J. Tol and J. van Heerden (2005), *Triple Dividends of Water Consumption Charges in South Africa*, **FNU-62**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. download

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Bosello, F., R. Roson and R.S.J. Tol(2004), *Economy-wide estimates of the implications of clima techange: Human health*, **FNU-57,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg.download

Hamilton, J.M. and M.A. Lau (2004), *The role of climate information in tourist destination choice decision-making*, **FNU-56,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. download

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Bigano, A., J.M. Hamilton, M. Lau, R.S.J. Tol and Y. Zhou (2004), *A global database of domestic and international tourist numbers at national and subnational level*, **FNU-54**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. download

Susandi, A. and R.S.J. Tol(2004), Impact *of international emission reduction on energy and forestry sector of Indonesia*, **FNU-53**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. download

Hamilton, J.M. and R.S.J. Tol (2004), *The Impact of Climate Change on Tourism and Recreation*, **FNU-52,**Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. download

Schneider, U.A. (2004), *Land Use Decision Modeling with Soil Status Dependent Emission Rates*, **FNU-51,** Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. download

Link, P.M., U.A. Schneider and R.S.J. Tol. (2004), *Economic impacts of changes in fish population dynamics: the role of the fishermen's harvesting strategies*, **FNU-50**, Centre for Marine and Climate Research, Hamburg University,Hamburg. download

Berritella, M., A. Bigano, R. Roson and R.S.J. Tol (2004), *A General Equilibrium Analysis of Climate Change Impacts on Tourism*, **FNU-49**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg. download

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Erdil, E. and I.H. Yetkiner (2004), *A Panel Data Approach for Income-Health Causality*, **FNU-47**, Centre for Marine and Climate Research, Hamburg University, Hamburg. download

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Zhou, Y. and R.S.J. Tol (2004), *Evaluating the costs of desalination and water transport*, **FNU-41**, revised, Centre for Marine and Climate Research, Hamburg University, Hamburg. download

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Bosello,F., Lazzarin, M., Roson, R. and Tol, R.S.J. (2004), *Economy-wide Estimates of the Implications of Climate Change: Sea Level Rise*, **FNU-38**, Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Schwoon, M. and R.S.J. Tol. (2004), *Optimal CO2-abatement with socio-economic inertia and induced technological change*, **FNU-37**,Centre for Marine and Climate Research, Hamburg University, Hamburg. download

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Tol, R.S.J. (2003), *Adaptation and Mitigation: Trade-offs in Substance and Methods*, **FNU-33,** Centre for Marine and ClimateResearch, Hamburg University, Hamburg. download

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Link, P.M. (2003), *Auswirkungen populationsdynamischer Veränderungen in Fischbeständen auf die Fischereiwirtschaft in der Barentssee,Research Unit Sustainability and Global Change,* **FNU-29**, Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Lau, M.A. (2003), *Integrated Coastal Zone Management in the People's Republic of China – An Assessment of Structural Impacts on Decision-making Processes, Research Unit Sustainability and Global Change,* **FNU-28(revised)**, Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Lau, M.A. (2003), *Coastal Zone Management in the People's Republic of China – A Unique Approach?*, **FNU-27**, Centre for Marine and Climate Research, Hamburg University, Hamburg. China Environment Series, Issue 6, pp. 120-124; download

Roson, R. and R.S.J. Tol (2003), *An Integrated Assessment Model of Economy-Energy-Climate – The Model Wiagem: A Comment*, **FNU-26**, Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Yetkiner, I.H. (2003), *Is There An Indispensable Role For Government During Recovery From An Earthquake? A Theoretical Elaboration*, **FNU-25**, Centre for Marineand Climate Research, Hamburg University, Hamburg. download

Yetkiner, I.H. (2003), *A Short Note On The Solution Procedure of Barro And Sala-i-Martin forRestoring Constancy Conditions*, **FNU-24**, Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Schneider, U.A. and B.A. McCarl (2003), *Measuring Abatement Potentials When Multiple Change is Present: The Case of Greenhouse Gas Mitigation in U.S. Agriculture and Forestry*, **FNU-23**, Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Zhou, Y. and R.S.J. Tol (2003), *The Implications of Desalination for Water Resources in China:An Economic Perspective*, **FNU-22**, Centre for Marineand Climate Research, Hamburg University, Hamburg. download

Yetkiner, I.H., de Vaal, A., and van Zon, A. (2003), *The Cyclical Advancement of Drastic Technologies*, **FNU-21**, Centre for Marine and Climate Research, Hamburg University, Hamburg. download

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Lee, H.C., B.A. McCarl, U.A.Schneider, and C.C. Chen (2003), *Leakage and Comparative Advantage Implications of Agricultural Participation in Greenhouse Gas Emission Mitigation*, **FNU-18**, Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Schneider, U.A. and B.A. McCarl(2003), *Implications of a Carbon Based Energy Tax for U.S. Agriculture,* **FNU-17**, Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Tol, R.S.J. (2002), *Climate, Development and Malaria: An Application of FUND*, **FNU-16**,Centre for Marine and Climate Research, Hamburg University, Hamburg. download

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Tol, R.S.J. (2002), *Technology Protocols for Climate Change: An Application of FUND*, **FNU-14**,Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Rehdanz, K (2002), *Hedonic Pricing of Climate Change Impacts to Households in Great Britain*, **FNU-13**, Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Tol, R.S.J. (2002), *Emission Abatement versus Development as Strategies to Reduce Vulnerability to Climate Change: An Application of FUND*, **FNU-12** (revised), Centre for Marine and Climate Research, Hamburg University, Hamburg. download

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Yohe, G. and R.S.J. Tol (2001), *Indicators for Social and Economic Coping Capacity – Moving Toward at Working Definition of Adaptive Capacity*, **FNU-8**,Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Kemfert, C., W. Lise and R.S.J. Tol (2001), *Games of Climate Change with International Trade*, **FNU-7**, Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Tol, R.S.J., W. Lise, B. Morel and B.C.C. van der Zwaan (2001), *Technology Development and Diffusion and Incentives to Abate Greenhouse Gas Emissions*, **FNU-6**, Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Kemfert, C. and R.S.J. Tol (2001), *Equity, International Trade and Climate Policy*, **FNU-5**,Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Tol, R.S.J., Downing T.E., Fankhauser S., Richels R.G. and Smith J.B. (2001), *Progress in Estimating the Marginal Costs of Greenhouse Gas Emissions*, **FNU-4**,Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Tol, R.S.J. (2000), *How Large is the Uncertainty about Climate Change?,* **FNU-3**,Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Tol, R.S.J., S.Fankhauser, R.G. Richels and J.B. Smith (2000), *How Much Damage Will Climate Change Do? Recent Estimates*, **FNU-2**,Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Lise, W. and R.S.J. Tol (2000), *Impact of Climate on Tourism Demand, Research Unit Sustainability and Global Change,* **FNU-1**,Centre for Marine and Climate Research, Hamburg University, Hamburg. download

Food production impacts of alternative global development scenarios

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Food production impacts of alternative global development scenarios

Abstract

Food and water resources are pressured by a growing human population which also becomes richer. Future generations will demand more food from fewer endowments of land and water. This study uses a global, partial equilibrium, and bottom-up model of the agricultural and forest sectors to quantify the food production impacts of four alternative development scenarios from the Millennium Ecosystem Assessment and the Special Report on Emission Scenarios. With unrestricted land expansion, productivity growth appears sufficient to counter increased commodity demand and resource scarcity in the next two and a half decades. Per-capita food levels increase with minor price changes. Global agricultural land increases up to 20 percent until 2030. Without land expansion, global per-capita food supply decreases between 6 and 12 percent. Across all scenarios, income developments are the dominating driver of development and lead to higher global average shares of non-vegetarian food. While irrigation increases steadily, agricultural water intensities peak for most scenarios in 2020 but decline afterwards. The bulk of food production increases occurs in Asian and Latin American regions. Developed regions and Sub-Saharan Africa have lower gains for optimistic and slight losses for pessimistic scenarios.

Keywords

land use economics; resource scarcity; irrigation; water; food security; population growth; income development; agricultural sector; forestry; mathematical programming; integrated assessment; bottom-up analysis; partial equilibrium; welfare maximization

Classifications

105.000 ENVIRONMENTAL PROBLEMS AND ISSUES – Land-use change;

107.200 ENVIRONMENTAL PROBLEMS AND ISSUES – Water scarcity;

205.000 BIOSPHERES AND ECOSYSTEM – Forests;

308.000 DISCIPLINE – Agriculture;

309.000 DISCIPLINE – Forestry;

404.000 MANAGEMENT OF THE ENVIRONMENT – Management and regulation;

500.000 HUMAN-BASED FIELDS WITHIN ENVIRONMENTAL SCIENCE;

602.000 TOOLS FOR ENVIRONMENTAL RESEARCH AND MANAGEMENT – Modelling;

603.000 TOOLS FOR ENVIRONMENTAL RESEARCH AND MANAGEMENT – Statistics/mathematical analysis;

701.000 COUNTRIES AND GEOGRAPHICAL REGIONS – General/global

Food production impacts of alternative global development scenarios

Food, land, and water constitute three of the most fundamental resources for mankind. These resources are under pressure by population growth, economic development, and global change. Essentially, more food may need to be produced with fewer resources. To analyze this predicament, we study alternative plausible development scenarios with a global, partial equilibrium, and bottom-up model of agriculture and forestry. Particularly, we quantify both partial and joint impacts of individual drivers on food supply. These drivers include land and water scarcity, technical progress, and food demand shifts due to population and income development. We examine the role of supply and demand adaptations related to land management intensity (irrigation) and the ratio of vegetarian to non-vegetarian food, respectively. Furthermore, we assess regional differences of development on per-capita food supply.

Resource scarcity is not a new phenomenon in human history. Growing populations in the past have caused local over exploitation of natural resources leading to the extinction or collapse of several ancient societies (Diamond 2005). However, today's resource scarcity is not only an acute problem in isolated locations, it is also a global threat. Three arguments may illustrate the global dimension of this threat. First, the collective use of resources for food production over all countries has reached substantial proportions. In 2005, agriculture occupied about 38 percent of the global land area (FAOSTAT 2005) yielding an average agricultural land endowment of 0.77 hectare per capita. Without technical progress and agricultural intensification and with current rates of population growth, agriculture would need an area equivalent to 1/2 and 2/3 of the current terrestrial land area by 2030 and 2070, respectively, in order to maintain current food consumption levels per capita. Similar calculations could be made with respect to fresh water and energy resources.

The second argument is that although some regions experience more challenges than others, today's societies are increasingly connected. Globalization opens the door to more international trade. Thus, regional commodity supply shortage or surplus can be transferred to and mitigated by world markets. Furthermore, globalization has reached governments. Since the establishment of the United Nations in 1945, many different international treaties have been adopted, which may particularly affect global food production and distribution. Environmental treaties relevant to food production include the convention on wetlands (RAMSAR convention), the Climate Change convention, and the convention on biological diversity (CBD convention). These treaties may limit possible expansion of agricultural land. However, expansion of cropland might be necessary to fulfill the eight millennium development goals defined by the world leaders at the United Nations Millennium Summit in 2002 since they include targets for the reduction of hunger and malnutrition.

A third argument is that the cumulative impacts of local land use decisions may cause significant global environmental feedback, foremost through climate change. There are both positive and negative agricultural impacts which influence the availability and fertility of land, the length of growing season, fresh water endowments, pest occurrence, CO_2-fertilization, and the frequency of extreme events related to draughts, flooding, fire, and frost.

Although global commodity trade and environmental policies are important drivers for resource utilization, a variety of additional factors influence the net impact of future development on land use and food supply. These factors include technical progress, land use intensities, land quality variations, resource endowments, and food demand characteristics. Technical progress and management intensification can reduce land scarcity. While improved technologies shift the production possibility frontier outwards, intensification moves production along a frontier by substituting one resource with another (Samuelson 1948). Irrigation, for example, increases water requirements but decreases land requirements per calorie. Intensification is often related to land but could be related to any other resource. Agricultural production can be intensified by employing more water, fertilizer, pesticides, machinery, or labor. Note that through intensification resources can become a substitute or complement. Similar antipodal effects can occur with commodity trade. Regional pressures on resource may decrease through commodity imports but increase due to specialization.

The variation of land quality also interacts with development. On the one hand, population growth increases food demand and therefore the demand for agricultural land.

Since rationally acting agents use the most suitable resource first, additional agricultural land is likely to be less productive. On the other hand, population growth increases predominantly urban land areas (United Nations 2004). This expansion potentially removes high quality agricultural areas since cities are usually built on fertile land (von Thünen 1875). Furthermore, increased agricultural intensity due to population growth may increase land degradation over time. This could trigger a positive feedback loop where increased degradation leads to more degradation through intensification. Fourth, income growth especially in low income regions raises demand for animal based food more than demand for vegetarian food. Since animal food production involves an additional element in the food chain, it may increase land requirements per calorie by a factor of 10 or more relative to vegetarian food (Gerbens-Leenes and Nonhebel 2005). Thus, an increased demand of animal food is likely to increase total agricultural land use and management intensities with the above described implications.

A global agricultural and forest sector optimization model

To assess interdependencies between population growth, economic and technological development, and the associated relative scarcities of land and water, we use a newly developed mathematical programming model of the global agricultural and forest sectors. The concept and mathematical structure of this model are similar to the US Agricultural Sector and Mitigation of Greenhouse Gas (ASMGHG) model (Schneider, McCarl and Schmid 2007). Like ASMGHG, the objective function simulates the global agricultural and forest market equilibrium by maximizing economic surplus over all included regions and commodities subject to exogenous resource endowments, technologies, and policies. The scope and resolution of regions, commodities, management options, and resources differs substantially from ASMGHG. Particularly, agricultural and forest product markets are represented by 27 international regions covering the entire world (Table 1). The definition of regions is consistent with the 11 large regions used in energy (Messner and Strubegger 1995) and pollution abatement models (Amann 2004,) of IIASA's Greenhouse Gas Initiative including as well as with the more detailed regions from the POLES model (Criqui et al. 1999) to facilitate future linkage with energy models in the context of climate and energy sustainability assessments.

Commodity demand is specified as downward-sloping function with constant elasticities. The model accounts for the annual net trade between all 27 regions. Demand data include observed prices, quantities of domestic demand, imports and exports, own-price and income elasticities of demand. For agricultural products, prices and quantities are taken from FAO (2007). Own-price and income elasticities of agricultural commodity demand are taken from Seale et al. (2003). The specification of demand for forest commodities is based on data developed by Rametsteiner *et al*. (2007). The model employs vertical factor supply functions in each region for a) the sum of agricultural and forest lands and b) land suitable for irrigation. Irrigation water supply is depicted as constant elasticity, upward-sloping function.

Agricultural production activities are portrayed in more detail than commodity markets and distinguish 160 individual countries, 37 agricultural and 4 forest commodities, and 5 irrigation alternatives (Table 2). Crop production data are taken from FAO (2007), where national averages over the years 1998-2002 are used to compute base levels for yields, harvested areas, prices, production, consumption, trade, and supply utilization. Irrigated crop yields, crop specific irrigation water requirements, and costs for five irrigation systems are derived from a variety of sources and are described in more detail in Sauer et al. (2008). Irrigation system capacities are computed for each country and depend on the distribution of soil types and slope (Skalsky et al. 2008, Sauer et al. 2008). Traditional forest management is based on the 4DSM model developed by Rametsteiner *et al*. (2007). Production costs are compiled from an internal database at IIASA's Forest Program.

Future development of agriculture and forestry is portrayed through recursive dynamics with exogenous adjustments to population, gross domestic product (GDP), technical efficiency, and policy parameters. Population and GDP changes shift demand curves for products and endowments for land and water. Land exchanges between agriculture and forestry are endogenous and the optimal land balance in a period serves as starting point for the next period. The model uses the year 2000 as starting point and computes a new equilibrium every ten years. For this study, we choose to terminate simulations in 2030. The current version of our model does not portray forest age structure and soil carbon dynamics.

When uncalibrated, large-scale land use optimization models are solved for the base period, they do not usually reproduce observed decisions. There are a variety of reasons for deviations. First, some data which influence land use decisions are difficult or impossible to obtain. These include impacts of crop rotations on yields, costs, labor, and machinery, which are often not available beyond a number of individual case studies. Second, some data are inaccurate because of measurement errors, inconsistent data collection methods, or insufficient resolution of the data. Third, our model operates at the sector level and does not explicitly portray many farm specific details, commodity qualities, and other local differences. Fourth, we assume competitive markets and rational behavior. To bring base solutions close to observation, we calibrate the direct costs for land management alternatives.

Following classical economic theory, we adjust the cost of each management option such that at base year commodity and factor prices, marginal revenues equal marginal costs (Wiborg et al. 2005). For crop production activities, this adjustment is performed on a weighted average between irrigated and rainfed crops, where the weights correspond to the estimated irrigation shares in the base year 2000. Trade costs for observed trading routes are set equal to the observed price difference between two trading partners. Trade costs for routes with zero trade in 2000 are computed via extrapolation from similar observed routes with the condition that the resulting level is not smaller than the price difference between importing and exporting country. Note that the base year calibration involves only linear cost adjustments.

Our modeling approach can be put in perspective with alternative methods. Previous land use assessments may be distinguished regarding a) the flow of information in top-down and bottom-up systems, b) the dominating analysis technique in engineering, econometric, and optimization approaches, c) the system dynamics in static equilibrium, recursive dynamic, and fully dynamic designs, d) the spatial scope in farm level, regional, national, multi-national, and global representations, and e) the sectoral scope in agricultural, forestry, multi-sector, and full economy models. Additional differences involve various modeling assumptions about market structure and the applied resolution over space, time, technologies, commodities, resources, and environmental impacts and associated data. For details on existing land use models, we refer to Lambin et al. (2000), Heistermann et al. (2006) and van der Werf and Peterson (2007). Applying classifications a) to e), our model can be characterized as bottom-up, optimization, recursive dynamic, global, agricultural and forest sector model.

Scenarios of Global Development

Development is a complex process involving numerous changes across all segments of society and its environment. Drivers of development involve both conscious societal choices and inherent characteristics of relevant systems. National and international policies may be considered as conscious choices. On the other hand, birth rates, labor productivities, speed of innovation, and consumer preferences are examples of rather inherent system characteristics, which are directly or indirectly influenced by conscious choices. To optimize development, policymakers need to be able to compare the consequences of alternative policies. The complexity and diversity of human societies and the earth system, however, does currently not allow such comparisons within a single model. In an effort, to consistently combine the insights from a variety of scientific models, several alternative development scenarios have been formulated which describe and quantify important aspects of development.

In this study, we consider four development scenarios, which were examined with several energy models in the context of the Energy Modeling Forum 22: Climate policy scenarios for stabilization and in transition. These include the scenarios *Global Orchestration*, *Order from Strength*, and *Adaptation Mosaic* of the Millennium Ecosystem Assessment (Carpenter and Pingali 2005) and a revised B1 baseline emission scenario of the Special Report on Emissions Scenarios (SRES, Nakicenovic and Swart 2000). Global Orchestration focuses on increased globalization emphasizing economic growth and public goods provision. The Order from Strength scenario has a regionalized approach focusing on national security and self-sustenance, whereas the Adapting Mosaic scenario focuses on local adaptation and flexible governance. The B1 scenario is characterized by increasing use of clean and efficient technologies with global-scale cooperation. Each scenario includes specific assumptions about population growth and migration, gross domestic product development, technical change, and environmental impacts.

For the four alternative pathways, we implement five important drivers of development: a) commodity demand growth due to population growth, b) commodity demand growth due to income change, c) technical progress, d) change in land endowments due to population growth, and e) change in fresh water availability due to population and income development. The impact of population growth on commodity demand is assumed to be strictly proportional. GDP changes, however, shift commodity demand according to income elasticities taken from Seale et al. (2003). Technical progress rates are commodity and country specific values compiled by the International Food and Policy Research Institute for each of the four EMF22 scenarios. Furthermore, the estimates of population and income growth are used to calculate supply shifts for land and water (Table 3). Land supply shifts are computed by dividing incremental increase in population by regional specific urban population densities. Similarly, water supply is decreased by the product of population increase and water use coefficients. We also apply a global income elasticity of 0.5 to reflect increased water demand as income grows (Dalhuisen et al. 2003).

To better distinguish the partial contribution of individual development drivers, we simulate each driver individually and jointly with all others. Furthermore, we separate two settings on possible land expansion. While the first setting allows expansion of croplands into native forests, the alternative only allows expansion of managed forests. In summary, we employ 4 basic development storylines, 2 land expansion alternatives, and compare 5 partial vs. 1 joint impact simulation. For each of these 48 combinations, we solve the global agricultural and forest sector model recursively from 2000 to 2030 in ten year increments.

Empirical Results

This section summarizes the simulation results from above-described scenarios. Because of the size of our model, we have to be selective. A single solution of our global agricultural and forestry sector model contains about 2.5 million variables and about 350 thousand marginal and slack values for equations. Accordingly higher is the output of

192 solutions. To provide a succinct summary within the scope of a journal article, we focus on aggregate measures. The use of aggregates has three additional advantages beyond brevity. First, as argued in Onal and McCarl (1991), sector models, while using more resolved data, perform better on the aggregated level. Second, aggregates implicitly contain many individual measures simultaneously. Third, the desirability of alternative development paths – in a potential Pareto optimality sense - can only be judged at the aggregated level.

Global Impacts of Development on Land, Water, and Food

Table 3 summarizes global land use impacts from simultaneous integration of exogenously given rates of technical progress, population growth, and GDP development. For each development pathway, the first row sections in Table 3 show the global magnitudes of these development parameters including their implications for land and water scarcity. By 2030, urbanization consumes an area roughly equivalent to 3 percent of the current agricultural area. Values differ slightly across development pathways depending on the assumed rates of population growth and estimated urban population densities. Non-agricultural water use increases between 228 km3 under Global Orchestration and 277 km3 under Order from Strength. Note, however, that all of these aggregates hide the underlying regional values, which may substantially differ across the four examined development pathways.

The next row sections in Table 3 show globally aggregated land allocations from the solution output of our model. If agricultural land expansion is allowed, global cropland increases by up to 20 percent until 2030. This expansion outpaces urbanization by several orders of magnitude after 2010. The revised B1 baseline scenario results in the highest land use change. For all scenarios with constrained agricultural land expansion, total cropland decreases beyond the loss from urbanization due to an increase in managed forest lands. The share of forest lands increases in all scenarios because demand shifts for forest commodities meet, in comparison to agriculture, lower supply shifts. This reflects the fact that technical progress rates for slowly growing trees are lower than those for annual food crops.

Irrigation constitutes one of the most influential adaptation option for farmers. According to Rosegrant et al. (2002), average irrigated yields of cereals are almost twice as high as average rainfed yields. The more water-deficient a region is, the higher are yield differences between irrigated and rainfed cropping systems. However, the decision to irrigate is influenced not only by local characteristics but also by international market feedbacks. Marginal revenues from irrigation depend on the product of yield differentials and commodity prices. Higher commodity prices increase the economic attractiveness of irrigation. On the other hand, increased water scarcity increases the marginal costs of irrigation. Table 3 shows the quantitative impacts of development on three measures: a) the change in irrigated area, b) the change in irrigation water use, and c) the change in average irrigation water intensities. We find increases in irrigated area and total agricultural water use across all development scenarios. If agricultural land expansion is allowed, the irrigated areas are higher than otherwise. The highest water use is found under Global Orchestration. However, the effect on irrigation water intensities is mixed. While restricted land expansion, steadily increases irrigation water intensities, values are much lower or negative under unrestricted land expansion. The changes in water intensity results from differences in irrigation water requirements across regions, crops, and irrigation systems.

Global food production impacts are also summarized in Table 3 and list the changes in total food production levels converted to food calories and the changes in real global food prices. Food production levels increase substantially but the magnitudes of these increases depend notably on the assumption about possible agricultural land expansion. In 2030, land expansion raises food supply between 7 and 8 percent for the three Millennium Assessment Scenarios and by 15 percent for the revised B1 SRES scenario. There is considerable variation across development pathways. The scenario with the lowest food supply under unrestricted land expansion (Order from Strength) supplies less food than the best scenario under restricted land expansion (Global Orchestration). Changes in global food prices reflect equilibrium adjustments from supply and demand shifts aggregated over all regions and food commodities. For unrestricted land expansion, food prices change only moderately. Restricted land expansion, however, leads to much higher food prices after 2010, especially for the revised B1 SRES scenario. These differences indicate a relatively strong sensitivity of prices to agricultural land endowments. It should be noted that we did not assess future demands for alternative land use, which may include demands for bioenergy plantations. Such additional demands would raise food prices even further.

Partial Impacts of Development on Global Food Production

The qualitative impacts of population growth, economic development, and technical progress are well-known. Increases in total food supply result from technical progress, demand increases, and expansion of agricultural land. In contrast, higher scarcities of agricultural resources cause negative impacts on food production. Population growth without income growth will increase total food production but decrease the per-capita level of food production because the required expansion of agricultural production implies increasing marginal costs.

This section quantifies the partial impacts of individual drivers of development on global food production for each of the examined four development storylines. We distinguish between impacts on vegetarian and non-vegetarian food because these two food types differ in three important aspects. First, vegetarian food generally requires much less land per calorie than does non-vegetarian food (Gerbens-Leenes and Nonhebel 2005). Second, positive income changes increase the demand for non-vegetarian food more than for vegetarian food. Thus, the net impact of development on the share of animal product based food is ambiguous. Third, the ratio between vegetarian and non-vegetarian food has important implications on the healthiness of the average diet. All tabulated values give the global per-capita food production relative to the situation in year 2000. To add more insight in our results, we compute per-capita food demand both relative to the population in year 2000 (Table 4) and relative to the projected population for each development pathway (Table 5).

The individual partial effects of land and water scarcity on per-capita food production show substantial decreases across all scenarios. The ratio between vegetarian and non-vegetarian food changes towards more vegetarian food. For example, in 2030, the Adapting Mosaic scenario leads to a 1.5 percent increase in vegetarian and a 12 percent decrease in non-vegetarian food. This happens as a result of 3 percent reduction in cropland due to urbanization. Surprisingly, the deforestation regulation has very little impact. Across the four storylines, the impacts are in accordance to the assumed growth in population. The land and water scarcity impact under the current population (Table 4) is more than doubled under the projected population in the respective year (Table 5).

The third partial impact shows the effects of increased food demand due to population growth. Technologies, income and resource levels are held at year 2000 values. If the food production impact of the demand shift is related to the year 2000 population (Table 4), per- capita supply of vegetarian food increases until 2030 up to 45 percent, while non-vegetarian food increases up to 15 percent. However, if food supplies are related to the projected population (Table 5), the per-capita levels of food production decrease. This happens as a result of increased marginal costs of agricultural production. For all scenarios, we find a substantial shift towards non-vegetarian food. This illustrates the adjustment of food production towards lower land intensities per calorie. The permission of land expansion (AgX1) increases food availability, however, the magnitudes of these increases are relatively small.

At first glance, the impacts of technical change on per-capita food production are quite low and therefore somewhat counterintuitive. If we compare our results to the year 2000 population (Table 4), we find, for example, a 2.3 percent increase in vegetarian food along with a 3.7 percent decrease in non-vegetarian food (2010, IIASA B1b, AgX0). However, because the global average share of non-vegetarian food in the base year is only 13 percent, the two changes together imply a net gain in food supply. The overall shift towards more vegetarian food is the complex outcome of a) differences in projected yield growth rates between crop and livestock commodities and b) regional differences in yield growth. If the food supply impacts of technical change are related to the projected population in each year (Table 5), the per-capita availability of food decreases across all scenarios. This implies that the negative impact of population growth on food security dominates the positive impact from technical change.

The last of the examined partial impacts of development is demand growth due to income (GDP) change. We observe a substantial increase in food production especially for the revised B1 and the Global Orchestration scenario. For these two storylines, the supply increases due to income based demand shifts more than offset the increased food needs of a growing population (Table 5). For the Order from Strength and the Adapting Mosaic, however, the income effect alone would not suffice to offset increasing food needs. Note again that the change in vegetarian food calories has higher weights than the change in non-vegetarian food. Across all income scenarios, we observe a substantial shift towards more animal food. This reflects the fact that income elasticities for animal non-vegetarian demand are considerably higher than those for vegetarian food.

The final row section in Table 4 and Table 5 shows the combined impacts of all individual development drivers. We find increases in per-capita food supply for all scenarios. The B1b and Global Orchestration scenarios dominate the remaining two scenarios by a large margin. Note that the combined effects exceed the partial effects of income based demand growth because in the combined scenario, the income shift is applied to a larger population.

Regional Food Production Impacts

While the previous section has shown overall positive food supply impacts of all four examined storylines, this section takes a closer look at regional differences. To ease this task, we aggregate the 27 model regions to 11 commonly used region groups. For each of these 11 groups, the impact of development on food supply is shown relative to the year 2000 population (Table 6) and relative to the projected population (Table 7). Values below 100 identify losses in per-capita food supply relative to the situation in year 2000. A quick glance over Table 7 reveals that several regions incur losses under some scenarios. For the revised B1b scenario, which has a high global benefit, some of the developed regions (North America, Western Europe, Pacific OECD) loose. These losses amount to as much as 20 percent if agricultural land expansion is restricted. The big winners of the B1b scenario are Asian countries including India and China, and South America. Sub-Saharan Africa benefits under B1b if agricultural land expansion is unrestricted. In this case, food supply increase by 27 percent until 2030.

Relatively balanced benefits across regions are found for the Global Orchestration pathway. Across the four alternatives, Global Orchestration produces the highest gains in many regions including the developed regions, Central Eastern Europe, the former Soviet Union, Southern and Pacific Asia, and Sub-Saharan Africa. For Sub-Saharan Africa, Global Orchestration is the only pathway that does not reduce the average per-capita food supply when land expansion is limited. Benefits to Latin America and China are even higher in absolute terms, however, these regions lose relative to the B1b pathway. The greater stability of changes across regions can be formally confirmed by computing the standard deviation across regions. Under Global Orchestration, this measure yields a 10 (limited land expansion) and 20 (unrestricted land expansion) percentage points lower value than under the revised B1 scenario.

The Order from Strength pathway shows for most regions an increase in food supply, which slightly exceeds the increase in demand. Hence, the per-capita availability of food remains fairly unchanged. China and Southern Asia achieve above-average values. Developed regions and Africa have slightly reduced per-capita food supply levels in 2030 under restricted land expansion. The assumption on land expansion creates a difference of roughly 10 percent by 2030 for most regions. For China, Latin America, and Sub-Saharan Africa, these differences are even higher. The variability of impacts under Order from Strength is lower than under B1b but slightly higher than under Global Orchestration. Across all four pathways, Order from Strength achieves the lowest per-capita food supply values in almost all regions and globally.

The fourth examined development pathway is called Adapting Mosaic and is characterized by relatively severe impacts of global change and a focus on local strategies. Trade barriers increase initially. The food production impacts of Adapting Mosaic are similar to the Order from Strength scenario. However, the relatively local approach also yields a few regions with somewhat better results. Especially, all Asian regions perform better than under Order from Strength. If land expansion is only economically restricted (AgX1), we observe similar values as before. In most regions, food supply increases by about 10 percentage points. Because all comparisons are made with respect to the per-capita situation in 2000, stagnating or slightly declining food supplies may not be a problem for North America and Western Europe. However, for Sub-Saharan Africa, this implies a continuation of nutritional deficiencies.

Summary and Conclusions

Global development imposes considerable challenges to international food production because additional agricultural resources come at increasing costs to markets and environment. To meet these challenges and to adequately consider the welfare of current and future generations, political interference is needed. However, efficient political interference requires scientific guidance through quantitative assessments to identify the best compromise between conflicting objectives. This paper uses a global, partial equilibrium, and bottom-up model of land use to assess these interdependencies between land, water, and food in the context of different global development scenarios. The chosen modeling approach differs both from relatively coarse macroeconomic assessments with top-down, computable general equilibrium models and from data rich geographic analyses, which keep market feedbacks exogenous.

From the application of this model to common development scenarios, we gain several insights. In absence of strong environmental policies, productivity growth appears sufficient to counter increased commodity demand and resource scarcity at the global level in the next two to three decades. Even without additional cropland, current levels of per-capita food production can be improved although global real food prices can more than double. Across all four examined development pathways, we find a dominance of income effects over resource scarcity, which increases the average share of non-vegetarian food. The complex interactions between different drivers of land use decisions cause non-linear impacts. Water intensities increase until 2020 but decrease thereafter. Regional gains and losses do not mimic average global changes. Sub-Saharan Africa only benefits under Global Orchestration or when land expansion is permitted. While Asian regions and Latin America have the highest gains in per-capita food supply in almost all development scenarios, changes in developed regions are moderate and can be slightly negative.

Several limitations to this work need to be mentioned. First, the solution values of mathematical programming models are point estimates without confidence interval. Second, the accuracy of model results depends on the quality of the data. The probability of undetected data errors decreases with the magnitude of an error. Third, our analysis does not portray adjustments in industrial sectors beyond the impacts contained in the exogenous GDP values. Fourth, our analysis ignores the dynamics of soil quality and the benefits of soil restoration and the losses from soil degradation. Fifth, possible climate change impacts on agriculture until 2030 are neglected.

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References

Amann M. (2004) The RAINS model. Documentation of the model approach prepared for the RAINS peer review 2004. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Carpenter S and P. Pingali (2005). Millenium ecosystem assessment—scenarios assessment. Island, Washington, DC.

Criqui, P., Mima, S., and L. Viguier. 1999. "Marginal abatement costs of CO2 emission reductions, geographical flexibility and concrete ceilings: an assessment using the POLES model." *Energy Policy* 27(10):585-601.

Dalhuisen,J.M., R.J.G.M.Florax, H.L.F.Groot, and P.Nijkamp. 2003. "Price and Income Elasticities of Residential Water Demand: A Meta-Analysis." *Land Economics*. 79:292-308.

Diamond, Jared (2005). *Collapse: How Societies Choose to Fail or Succeed*. New York: Viking Books. ISBN 1-586-63863-7.

FAOSTAT. 2005. Available online at faostat.fao.org.

Gerbens-Leenes,W. and S.Nonhebel. 2005. "Food and land use. The influence of consumption patterns on the use of agricultural resources." *Appetite*. 45:24-31.

Heistermann,M., C.Muller, and K.Ronneberger. 2006. "Land insight? Achievements, deficits and potentials of continental to global scale land-use modeling." *Agriculture Ecosystems & Environment*. 114:141-158.

Lambin,E.F., M.D.A.Rounsevell, and H.J.Geist. 2000. "Are agricultural land-use models able to predict changes in land-use intensity?" *Agriculture, Ecosystems & Environment*. 82:321-331.

Messner, S., Strubegger, M., 1995: User's Guide for MESSAGE III, WP-95-69, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Nakicenovic N. and Swart, R.J. (2000) Emissions Scenarios 2000 – Special Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

Onal,H. and B.A.Mccarl. 1991. "Exact Aggregation in Mathematical-Programming Sector Models." *Canadian Journal of Agricultural Economics-Revue Canadienne D Economie Rurale*. 39:319-334.

Rametsteiner, E., S. Nilsson, H. Boettcher, P. Havlik, F. Kraxner, S. Leduc, M. Obersteiner, F. Rydzak, U.A. Schneider, D. Schwab, L. Willmore (2007). Study of the Effects of Globalization on the Economic Viability of EU Forestry. Final Report of the AGRI Tender Project: AGRI-G4-2006-06 [2007]. http://ec.europa.eu/agriculture/analysis/external/viability_forestry/index_en.htm

Rosegrant M.W., X. Cai and S.A. Cline, *Global Water Outlook to 2025: Averting an Impending Crisis*, A Report Summary of the 2020 Vision for Food, Agriculture and the Environment Initiative, International Food Policy Research Institute, Washington DC and International Water Management Institute, Colombo, 2002

Paul A. Samuelson. 1948 “International Trade and the Equalisation of Factor Prices”, *The Economic Journal* 58(230):163-184.

Sauer, T., Havlik, P., Kindermann, G., and Schneider, U.A. 2008. Agriculture, Population, Land and Water Scarcity in a changing World - the Role of Irrigation. Paper prepared for the 2008 Congress of the European Association of Agricultural Economists in Gent, Belgium.

Schneider,U.A., B.A.McCarl, and E.Schmid. 2007. "Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry." *Agricultural Systems*. 94:128-140.

Seale, J., A. Regmi, and J. Bernstein 2003. “International Evidence on Food Consumption Patterns.” ERS/USDA, Technical Bulletin No.1904, ERS/USDA, Washington, D.C.

Skalsky, R., Z. Tarasovičová, J. Balkovič, E. Schmid, M. Fuchs, E. Moltchanova, G. Kindermann, and P. Scholtz. 2008. GEO-BENE global database for bio-physical modeling v. 1.0 – concepts, methodologies and data. The GEO-BENE database report. International Institute for Applied Systems Analysis (IIASA), Austria, pp. 58.

Skalsky, R., Z. Tarasovičová, J. Balkovič, E. Schmid, M. Fuchs, E. Moltchanova, G. Kindermann, and P. Scholtz. 2008. GEO-BENE global database for bio-physical modeling v. 1.0 – concepts, methodologies and data. The GEO-BENE database report. International Institute for Applied Systems Analysis (IIASA), Austria, pp. 58.

United Nations. 2004. World urbanization prospects: The 2003 revision. Department of Economic and Social Affairs, Population Division, New York

Van der Werf, E. & Peterson, S. (2007), “Modeling linkages between climate policy and land use: An overview”. FEEM Working Papers 56.2007, Fondazione Eni Enrico Mattei, Milano, Italy.

von Thünen, Jh.H. 1875. Der isolierte Staat in Beziehung auf Landwirtschaft und Nationalökonomie. Eds. Hermann Schumacher, 3. Edition, Wiegandt, Hempel & Parey, Berlin. p 400.

Wiborg, T., B.A. McCarl, S. Rasmussen, and U.A. Schneider (2005), "Aggregation and Calibration of Agricultural Sector Models Through Crop Mix Restrictions and Marginal Profit Adjustments."

Table 1 Geopolitical Resolution

Model Region	Contained Countries
CANADA	Canada
USA	USA
MEXICO	Mexico
CENTR_AMER	Bahamas, Barbados, Belize, Bermuda, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Antilles, Nicaragua, Panama, St. Lucia, St. Vincent, Trinidad Tobago
SOUTH_AMER	Argentina, Bolivia, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela
BRAZIL	Brazil
ROWE	Gibraltar, Iceland, Norway, Switzerland
EU_NORTH	Denmark, Finland, Ireland, Sweden, United Kingdom
EU_MIDWEST	Austria, Belgium, France, Germany, Luxembourg, Netherlands
EU_BALTIC	Estonia, Latvia, Lithuania
EU_SOUTH	Cyprus, Greece, Italy, Malta, Portugal, Spain
EU_CENTREAST	Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia
EU_OTHER	Albania, Bosnia Herzegovina, Croatia, Macedonia, Serbia-Montenegro
TURKEY	Turkey
MIDEAST_NAFR	Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syria, Tunisia, United Arabic Emirates, Yemen
SUBSAH_AFR	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Democratic Republic of the Congo, Republic of the Congo, Ivory Coast, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Martinique, Mauritania, Mozambique, Niger, Nigeria, Rwanda, São Tomé and Príncipe, Senegal, Seychelles, Sierra Leone, Somalia, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
SOUTH_AFRICA	South Africa
FORMER_USSR	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
RSAS	Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan, Sri Lanka
INDIA	India
CHINA	China
JAPAN	Japan
RSEA_PAC	Cambodia, North Korea, Laos, Mongolia, Vietnam,
S_KOREA	South Korea
RSEA_OPA	Brunei, Indonesia, Malaysia, Myanmar, Philippines, Singapore, Thailand
AUSTRALIA	Australia, New Zealand
PACIFIC_ISL	Fiji Islands, Kiribati, Papua New Guinea, Samoa, Solomon Islands, Tonga, Vanuatu

Table 2 Agricultural Scope

Index	**Elements**
Land Use Types	Arable and grass lands, managed forests, native forests
Explicit Resources	Land, irrigation land, water
Crops	Agave fibers, banana, barley, broad horse beans, cassava, chickpeas, coconut, coffee, corn, cotton, dry beans, flax, groundnuts, jute, lentils, linseed, melon seed, millet, mustard seed, olives, oil palm fruit, plantain, peas, pulses, potatoes, rapeseed, rice, safflower seed, soya, sorghum, sesame seed, sugar beet, sugarcane, sunflower, sweet potatoes, wheat, yams
Livestock Products	Animal food calories with fixed proportions of bovine meat, pig meat, sheep and goat meat, chicken meat, equine meat, fresh milk, turkey meat, and eggs from hens and other birds
Forest Commodities	Sawn wood, wood pulp, fuel wood, other industrial wood
Management	Dryland, furrow irrigation, sprinkler irrigation, drip irrigation, surface irrigation

Table 3 Land Use Impacts of Global Development on Agriculture and Forestry[i]

Agricultural Impact	Year	IIASA B1b AgX0	IIASA B1b AgX1	MA GlbOrc AgX0	MA GlbOrc AgX1	MA OrdStr AgX0	MA OrdStr AgX1	MA AdpMos AgX0	MA AdpMos AgX1
Population [Billion]	2000	6.01		6.11		6.11		6.11	
	2010	6.84		6.77		6.99		6.99	
	2020	7.56		7.32		7.85		7.83	
	2030	8.13		7.74		8.57		8.53	
Gross Domestic Product [$1000/cap]	2000	4.47		4.73		4.73		4.73	
	2010	5.25		5.79		5.24		5.26	
	2020	6.83		7.76		6.02		6.16	
	2030	8.89		10.53		6.81		7.37	
Urbanization [Mill ha]	2010	14.32		12.25		15.14		15.14	
	2020	27.08		23.07		30.00		29.78	
	2030	37.38		31.99		42.67		42.02	
Change in Non-Ag Water Use [km3]	2010	96.8		85.6		101.7		101.7	
	2020	182.8		163.8		200.4		199.4	
	2030	249.5		227.6		276.8		274.8	
Change in Cropland Area [Mill ha]	2000	1348 (Total Area)							
	2010	-15.8	-11.2	-13.7	-13.7	-16.6	-16.6	-16.6	-16.6
	2020	-34.9	84.1	-30.9	20.8	-37.8	24.1	-37.6	32.9
	2030	-60.2	266.1	-54.9	100.2	-65.5	101.4	-64.9	137.5
Change in Managed Forests [Mill ha]	2000	732 (Total Area)							
	2010	1.5	1.4	1.5	1.5	1.5	1.4	1.5	1.4
	2020	7.8	7.3	7.8	7.4	7.8	7.3	7.8	7.3
	2030	22.9	19.8	22.9	20.8	22.9	20.7	22.9	20.6
Change in Irrigation Area [Mill ha]	2010	145	168	129	145	142	159	142	163
	2020	190	259	171	207	168	214	171	219
	2030	193	334	168	261	156	245	165	275
Change in Water Use for Irrigation [km3]	2010	131	114	116	100	163	137	163	135
	2020	240	268	215	194	204	203	206	212
	2030	230	273	243	288	166	187	189	248
Change in Water Intensity [m3/ha]	2010	35.1	-39.0	31.4	-32.3	94.3	15.3	95.7	6.0
	2020	151.5	86.2	139.7	41.7	124.9	47.2	124.4	54.5
	2030	130.9	3.0	189.8	114.4	78.9	-18.1	104.0	37.3
Food Supply [1E18 Cal]	2000	6.94							
	2010	8.48	8.59	8.67	8.71	8.56	8.60	8.62	8.67
	2020	10.19	10.68	10.50	10.92	9.88	10.26	10.09	10.52
	2030	11.86	13.62	12.72	13.61	11.02	11.92	11.70	12.72
Crop Price [Fisher Index]	2000	100.0							
	2010	100.9	97.5	93.5	92.4	98.2	96.0	98.3	96.0
	2020	133.6	109.4	106.0	94.6	114.0	100.7	117.6	101.5
	2030	240.3	127.3	138.6	101.3	150.7	108.8	165.6	113.1

Table 4 Partial Impacts of Global Development on Global Food Supply Relative to Year 2000 Population

Development Impact	Food Type	Year	IIASA B1b		MA GlbOrc		MA OrdStr		MA AdpMos	
			AgX0	AgX1	AgX0	AgX1	AgX0	AgX1	AgX0	AgX1
Land Scarcity (L)	Vegetarian	2010	99.0	99.0	100.4	100.4	100.7	100.7	100.7	100.7
		2020	98.3	98.3	100.8	100.8	101.4	101.4	101.4	101.4
		2030	97.3	97.3	100.8	100.8	101.6	101.7	101.5	101.6
	Non-Vegetarian	2010	95.6	95.6	96.6	96.6	95.1	95.1	95.1	95.1
		2020	92.4	92.4	94.3	94.3	91.4	91.4	91.4	91.4
		2030	90.0	90.0	92.9	92.9	88.0	88.0	88.2	88.5
Water Scarcity (W)	Vegetarian	2010	99.4	99.4	100.8	100.8	101.1	101.1	101.1	101.1
		2020	98.8	98.8	101.3	101.3	101.9	101.9	101.9	101.9
		2030	98.3	98.3	101.7	101.7	102.5	102.5	102.5	102.5
	Non-Vegetarian	2010	95.6	95.6	96.6	96.6	95.1	95.1	95.1	95.1
		2020	92.4	92.4	94.3	94.3	91.4	91.4	91.4	91.4
		2030	90.2	90.2	93.1	93.1	88.2	88.2	88.5	88.5
Population Growth (P)	Vegetarian	2010	111.7	112.1	111.2	111.3	114.9	115.5	114.9	115.5
		2020	120.8	122.6	119.4	120.4	127.9	130.2	127.6	129.9
		2030	127.7	131.8	125.5	127.6	139.1	144.2	138.3	143.1
	Non-Vegetarian	2010	104.7	104.9	104.2	104.2	104.4	104.7	104.4	104.7
		2020	108.6	108.8	107.9	107.9	109.1	109.6	109.1	109.6
		2030	111.3	112.7	111.1	111.5	111.8	114.0	112.0	114.0
Technical Progress (T)	Vegetarian	2010	102.3	102.3	104.5	104.5	103.9	103.9	104.0	104.0
		2020	104.4	104.3	108.8	108.8	107.4	107.4	107.8	107.7
		2030	106.3	106.3	113.3	113.3	110.5	110.4	110.9	110.9
	Non-Vegetarian	2010	96.3	96.3	97.5	97.5	95.8	95.8	95.8	95.8
		2020	93.9	93.9	96.3	96.3	92.9	92.9	92.9	92.9
		2030	91.9	91.9	95.6	95.6	89.9	89.9	90.7	90.7
Income Change (I)	Vegetarian	2010	104.4	105.0	106.7	107.0	104.8	104.9	105.5	105.6
		2020	108.5	111.7	113.3	116.2	109.3	110.2	110.8	111.9
		2030	114.5	124.4	121.1	129.2	113.7	115.6	117.8	121.5
	Non-Vegetarian	2010	121.8	122.3	122.1	122.4	111.1	111.1	113.0	113.0
		2020	167.4	169.6	162.2	164.4	126.8	127.0	133.7	134.2
		2030	228.7	239.0	223.3	233.7	143.0	144.7	162.9	165.4
All of Above (LWPIT)	Vegetarian	2010	120.4	122.1	122.9	123.5	123.1	123.9	123.8	124.7
		2020	138.5	146.4	145.2	151.6	142.9	148.8	145.1	151.8
		2030	151.3	178.9	168.3	182.5	160.4	174.9	167.1	183.5
	Non-Vegetarian	2010	134.1	134.8	133.2	133.2	123.1	123.3	125.3	125.6
		2020	198.8	202.9	190.4	193.4	153.3	155.3	162.2	164.4
		2030	281.9	308.1	283.5	290.4	185.0	191.6	211.3	219.7

Table 5 Partial Impacts of Global Development on Global Food Supply Relative to Projected Population

Development Impact	Food Type	Year	IIASA B1b AgX0	IIASA B1b AgX1	MA GlbOrc AgX0	MA GlbOrc AgX1	MA OrdStr AgX0	MA OrdStr AgX1	MA AdpMos AgX0	MA AdpMos AgX1
Land Scarcity (L)	Vegetarian	2010	87.8	87.8	90.1	90.1	87.2	87.2	87.2	87.2
		2020	79.3	79.3	83.2	83.1	77.5	77.6	77.7	77.7
		2030	73.5	73.5	78.4	78.4	70.6	70.6	71.0	71.0
	Non-Vegetarian	2010	87.9	87.9	90.1	90.1	87.2	87.2	87.2	87.2
		2020	79.5	79.5	83.2	83.2	77.8	77.8	77.8	77.8
		2030	73.8	73.8	78.5	78.8	70.9	70.9	71.4	71.4
Water Scarcity (W)	Vegetarian	2010	88.2	88.2	90.5	90.5	87.6	87.6	87.6	87.6
		2020	79.8	79.8	83.7	83.7	78.0	78.0	78.2	78.2
		2030	74.3	74.3	79.2	79.2	71.4	71.4	71.8	71.8
	Non-Vegetarian	2010	87.9	87.9	90.1	90.1	87.2	87.2	87.2	87.2
		2020	79.5	79.5	83.2	83.2	77.8	77.8	77.8	77.8
		2030	74.1	74.1	78.8	78.8	71.1	71.1	71.4	71.4
Demand Shift due to Population Growth (P)	Vegetarian	2010	98.5	98.8	99.5	99.6	99.0	99.5	99.0	99.5
		2020	95.7	97.1	97.7	98.5	96.0	97.8	96.1	97.8
		2030	93.5	96.3	96.2	97.8	93.3	96.9	93.6	97.0
	Non-Vegetarian	2010	95.8	95.8	97.0	97.0	95.3	95.6	95.3	95.6
		2020	91.9	92.1	94.3	94.6	91.1	91.6	91.1	91.6
		2030	88.6	89.6	92.8	93.3	86.7	88.4	87.2	88.9
Technical Progress (T)	Vegetarian	2010	90.6	90.6	93.7	93.7	90.0	90.0	90.0	90.0
		2020	83.8	83.7	89.6	89.6	82.0	82.0	82.4	82.3
		2030	79.3	79.3	87.6	87.6	76.4	76.4	77.1	77.1
	Non-Vegetarian	2010	88.4	88.4	90.9	90.9	87.9	87.9	87.9	87.9
		2020	80.5	80.5	84.9	84.9	78.8	78.8	79.0	79.0
		2030	75.3	75.3	80.7	80.7	72.3	72.3	72.8	72.8
Demand Shift due to Income Change (I)	Vegetarian	2010	92.7	93.2	95.8	96.1	90.8	90.8	91.3	91.4
		2020	87.8	90.4	93.4	95.9	83.4	84.2	84.7	85.6
		2030	87.9	94.9	94.2	100.5	78.7	80.1	81.9	84.6
	Non-Vegetarian	2010	112.1	112.6	113.8	114.3	102.0	102.0	103.7	103.7
		2020	144.2	146.2	143.7	145.7	108.1	108.4	113.6	114.3
		2030	188.4	197.0	191.6	200.5	115.6	117.0	131.4	133.1
All of Above (LWPIT)	Vegetarian	2010	106.2	107.7	110.1	110.6	106.2	106.8	106.8	107.5
		2020	110.2	116.1	119.0	124.4	107.3	111.9	109.2	114.4
		2030	113.0	131.6	129.3	140.0	107.7	117.5	113.2	124.2
	Non-Vegetarian	2010	122.7	123.5	124.0	124.0	112.6	112.6	114.3	114.6
		2020	168.9	172.6	167.7	170.1	128.4	129.9	135.8	137.5
		2030	225.4	246.7	240.5	246.2	144.4	149.6	165.2	171.4

Table 6 Impact of Development and Regional Food Production Relative to Year 2000 Population (LWPIT Scenarios)[ii]

Region	Year	IIASA B1b		MA GlbOrc		MA OrdStr		MA AdpMos	
		AgX0	AgX1	AgX0	AgX1	AgX0	AgX1	AgX0	AgX1
North America	2010	112.7	118.3	121.8	122.3	118.8	120.1	118.2	119.5
	2020	106.1	113.2	121.1	139.9	114.5	127.8	112.5	126.0
	2030	101.4	120.9	132.3	144.6	120.0	131.5	116.6	128.8
Western Europe	2010	107.6	109.1	111.9	112.6	107.2	107.7	106.9	107.4
	2020	105.3	112.3	119.1	124.0	110.1	115.1	108.4	114.4
	2030	95.1	114.6	123.4	135.4	108.1	119.8	105.7	119.1
Pacific OECD	2010	107.6	109.3	112.4	113.4	106.4	107.6	106.0	107.5
	2020	103.7	110.0	114.7	119.1	103.9	108.9	102.5	108.7
	2030	98.0	111.4	115.2	125.9	98.6	107.9	98.4	108.3
Central Eastern Europe	2010	114.3	115.6	109.4	109.7	102.9	103.5	103.6	104.4
	2020	120.3	126.8	117.3	121.8	98.5	103.2	100.1	106.1
	2030	117.1	141.0	124.0	134.8	91.7	102.6	97.7	107.3
Former Soviet Union	2010	105.4	106.7	116.4	116.6	109.7	109.8	111.0	111.1
	2020	117.1	122.9	128.9	133.2	112.2	115.7	113.9	119.7
	2030	119.6	149.1	145.9	154.1	111.4	121.0	116.7	129.2
Planned Asia and China	2010	127.7	130.3	126.4	127.5	119.9	121.0	121.8	123.0
	2020	160.7	168.9	160.9	168.5	135.2	142.4	142.2	150.1
	2030	196.0	232.6	197.9	211.1	145.3	161.5	164.3	181.1
South Asia	2010	121.3	121.2	127.7	127.7	129.8	129.8	131.1	131.1
	2020	149.8	151.3	165.5	165.8	162.9	163.3	167.8	168.4
	2030	185.4	191.9	221.6	222.9	197.0	199.2	214.1	216.6
Other Pacific Asia	2010	121.4	124.0	129.4	130.1	126.1	127.7	127.4	129.3
	2020	137.2	153.3	160.8	172.9	148.6	158.3	153.1	164.7
	2030	136.7	179.3	184.2	220.5	160.8	190.6	169.7	210.5
Middle East and Northern Africa	2010	137.5	137.9	128.5	128.6	131.5	131.7	132.0	132.1
	2020	172.2	181.2	152.2	157.1	154.6	161.1	155.1	161.3
	2030	194.6	243.6	164.2	182.8	164.6	182.9	162.7	183.8
Latin America and Caribbean	2010	130.6	132.5	121.0	121.6	123.3	124.1	124.0	124.8
	2020	175.1	190.6	144.4	152.9	146.4	154.9	147.6	157.8
	2030	197.1	245.9	163.9	189.9	160.9	186.8	162.7	193.4
Sub-Saharan Africa	2010	138.8	141.5	127.5	128.8	129.1	131.2	129.4	131.3
	2020	172.0	186.6	150.9	160.9	155.6	165.7	154.9	165.9
	2030	197.7	252.6	170.7	202.0	180.8	210.2	178.5	209.2

Table 7 Impact of Development and Regional Food Production Relative to Projected Population (LWPIT Scenarios)

Region	Year	IIASA B1b		MA GlbOrc		MA OrdStr		MA AdpMos	
		AgX0	AgX1	AgX0	AgX1	AgX0	AgX1	AgX0	AgX1
North America	2010	105.3	110.6	113.3	113.8	110.9	112.2	110.4	111.6
	2020	91.7	97.7	103.8	120.4	98.6	110.4	96.9	109.0
	2030	81.9	97.5	105.2	115.1	97.3	106.6	94.7	104.4
Western Europe	2010	103.5	105.0	107.0	107.7	103.9	104.4	103.7	104.2
	2020	98.5	105.0	108.2	112.5	102.7	107.2	101.0	106.3
	2030	87.0	104.7	106.9	116.9	98.0	108.0	95.2	106.4
Pacific OECD	2010	102.5	104.2	107.6	108.4	104.1	105.3	103.8	105.1
	2020	96.9	102.6	105.6	109.3	102.6	107.0	100.8	106.4
	2030	90.4	102.2	101.9	110.7	99.9	108.2	97.6	106.6
Central Eastern Europe	2010	110.9	112.1	109.5	109.9	104.9	105.5	105.7	106.5
	2020	116.7	123.0	118.7	123.3	105.4	110.5	106.6	113.0
	2030	114.8	138.2	128.1	139.3	105.4	117.9	110.3	121.1
Former Soviet Union	2010	101.7	102.9	114.7	114.9	108.1	108.2	109.4	109.5
	2020	110.7	116.2	126.2	130.4	111.2	114.7	112.6	118.3
	2030	112.1	139.7	143.5	151.6	112.8	122.5	116.9	129.4
Planned Asia and China	2010	120.2	122.6	119.7	120.8	110.9	111.9	112.7	113.8
	2020	146.2	153.5	147.9	154.9	117.5	123.7	123.7	130.5
	2030	177.5	210.4	181.0	192.9	122.6	136.1	139.3	153.2
South Asia	2010	105.8	105.7	111.0	111.0	106.6	106.6	107.6	107.6
	2020	117.0	117.9	129.3	129.6	113.9	114.1	117.6	118.0
	2030	135.2	138.8	161.5	162.5	122.1	123.5	134.1	135.6
Other Pacific Asia	2010	107.5	109.7	115.8	116.4	108.5	109.8	109.6	111.2
	2020	110.5	123.4	133.0	142.9	112.5	119.7	116.2	124.9
	2030	103.1	134.7	143.8	171.8	110.5	130.7	117.7	145.4
Middle East and Northern Africa	2010	105.4	105.7	108.3	108.3	106.0	106.1	106.3	106.5
	2020	108.2	113.8	112.3	115.9	103.8	108.1	104.3	108.6
	2030	105.0	131.4	109.9	122.3	97.3	108.1	96.6	109.1
Latin America and Caribbean	2010	114.0	115.7	107.3	107.8	103.8	104.5	104.4	105.1
	2020	137.5	149.7	116.8	123.7	106.4	112.6	107.5	115.0
	2030	143.5	179.1	123.8	143.4	104.7	121.5	106.3	126.3
Sub-Saharan Africa	2010	102.3	104.2	104.8	105.8	101.5	103.1	101.8	103.2
	2020	101.8	110.4	107.9	115.0	99.8	106.2	99.8	106.8
	2030	99.4	126.9	109.7	129.7	96.0	111.6	96.5	113.1

[i] MA = Millenium Ecosystem Assessment, GlbOrc = Global Orchestration, OrdStr = Order from Strength, AdpMos = Adapting Mosaic

[ii] Results from the 27 model regions are aggregated to a commonly used 11 region classification.

The interdependencies between food and biofuel production in European agriculture – an application of *EUFASOM*

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Abstract

In the continuous quest to reduce anthropogenic emissions of carbon dioxide, the production and use of organically grown fuels in Europe has increased in importance in the recent past. However, the production of so-called biofuels is a direct competitor of agricultural food production for land, labor, water resources etc. with both land use options influencing each other depending on the respective boundary conditions defined by political regulations and economic considerations. In this study we will explore the economic and technical potentials of biofuels in Europe as well as the interdependencies between these two land use options for different economic incentives for biofuels using the European Forest and Agriculture Sector Optimization Model (*EUFASOM*). Key data on biodiesel and ethanol production have been gathered and are used for calibration of the model. The simulations extend until the year 2030, for which results are presented. Results indicate that moderate production targets of biofuels lead to an expansion of mainly the biodiesel production while more ambitious targets call for a focus on bioethanol. This has to do with the different levels of production efficiency depending on the production output. Growth of bioethanol feedstock is spread over entire Europe while the production of biodiesel feedstock occurs mainly in Central Europe.

1 Introduction

The current European energy supply depends to a large extent on imported fossil fuels. This dependence, which is supposed to increase carries possible geopolitical risks in the future, also there are many possible environmental and health related hazards associated with the combustion of these fuels and the emissions of their pollutants as well as greenhouse gases. The European Union has committed itself to achieve, under all circumstances, a reduction of greenhouse gas emissions of at least 20% in comparison to 1990 by the year 2020 (EU Commission, 2007a).

Fuels derived from biomass are considered an alternative renewable energy source, which is claimed to have several advantages in comparison to fossil energy sources. It is a possible means to reduce greenhouse gas emissions (Fernside, 1999; McCarl & Schneider, 2000). Also, biomass adds humus to the soil and reduces erosion, thus increased biomass production can improve soil quality of agricultural land (Hoogwijk et al., 2003). However, it is unclear, how effective biofuels can be as a substitute for fossil fuels. Hoogwijk and others (2003) have estimated guardrails for the global potential of biomass use in energy production. Depending on the demographic and economic development in the next few decades, the global biomass potential spans three orders of magnitude.

The conditions, under which biofuels can become a competitive alternative on the energy market, have been explored in recent studies. A partial equilibrium model is applied to assess substitution mechanisms between fossil and biofuels and their possible impacts on greenhouse gas emissions and agricultural land use (Ignaciuk et al., 2006). Greenhouse gas emissions can be substantially reduced by a combination of a tax on fossil fuels and a subsidy of biofuels. However, the overall development of welfare is generally negative. McCarl et al. (2000) focus on the agricultural sector using an early version of the *FASOM* (Forest and Agriculture Sector Optimization Model) model. The results indicate that the degree of competitiveness of biofuels is dependent on the success of improving the production efficiency of the necessary crops. For this, short-rotation woody crops appear to be the most suitable crops for energy production.

There are certain thresholds below which biofuels cannot be competitive in the energy sector. Johansson and Azar (2007) analyze the connection between food and energy prices for two different U.S. climate policies using a non-linear dynamic optimization model. Based on their assessment, bioenergy production becomes competitive already at approximately $20 per ton of carbon, which is the same magnitude as the results obtained in Azar (2005), Schneider and McCarl (2003) and McCarl and Schneider (2001). Schneider and McCarl (2003) find that carbon prices of approximately $40 per ton of carbon equivalent are necessary for biofuels to become competitive. Above this carbon price, biofuels can offset emissions from fossil fuels. If prices increase even further, biofuels become the predominant means of emission mitigation at $70 per ton of carbon equivalent. These figures are substantially lower than the average abatement costs for bioethanol, which lie between $250 and $330 per ton of carbon (Jerko, 1996). A recent study focusing on Europe is less optimistic. The subsidies for biofuels necessary to reduce a unit of carbon emissions are found to be between more than € 200 for biodiesel and up to € 800 for bioethanol (Kutas et al., 2007). The emission reduction brought about by the same financial investment could be up to 20 times as high if instead funds were invested in emission offsets at the European Climate Exchange.

Due to the close interdependencies of the economics of food and non-food agriculture, any policy of further development of bioenergy production should always be considered in conjunction with agricultural food production. E.g. since the amount of land that can be used for bioenergy production is limited, there is a constant competition between agricultural food production and bioenergy production for this resource. A continued expansion of biofuels production will therefore have a lasting impact on agricultural land use patterns worldwide.

One important aspect to consider is the fact that the different biofuel feedstocks require different amounts of land for each unit of biofuel produced. All other factors being equal, the production of bioethanol requires less agricultural land than the production of biodiesel (Kavalov, 2004). This is because the bioethanol yield in the EU-15 countries is generally much higher than the biodiesel yield. Therefore, a focus of biofuel production on bioethanol would drastically reduce the amount of land required for biofuel production in the next few years. E.g. only 7 to 9% of the arable farm land in the EU-15 countries would be required to fulfill the future EU target if the entire biofuel production focused on bioethanol.

Currently, bioethanol still has the greatest significance among all biofuels on a global scale (EU Commission, 2006). In 2004, about 30 billion liters were produced worldwide. This amounts to roughly 2% of the total fuel use. However, biodiesel, which used to be produced exclusively in the EU, is now gaining importance in other parts of the world as well, thus increasing its relative importance in the bioenergy sector. At present, Germany, France and Italy are the main producers of biodiesel, leading the EU-25 production of close to 2 million tons in 2004. In contrast, biogas is only of regional significance, mainly in Scandinavia. An expansion of biofuel feedstock production to reach EU targets in the next years requires additional agricultural land to be set aside for bioenergy production (EU Commission, 2007b). Based on model simulations, about 40% of the additional land will need to be taken from land that was formerly set aside. Almost as much land will have to be shifted from production for exports to production for the domestic market. In conjunction, it is expected that market prices of agricultural goods increase. However, the intensity of agricultural production is expected to remain more or less unaffected, as there is little room for further intensification of agriculture in Europe.

The increased importance of biofuel production in Europe is the consequence of the EU policy on alternatives to fossil fuels, which attempts to decrease the reliance on fossil energy sources in the next decades. The first target of the EU strategy to increase the share of biofuels in the energy sector was at 2% in 2005 (Kavalov, 2004). This target could be easily reached, as enough agricultural land is available in all EU countries to produce the necessary amount of biomass. The next target is set for 2010, when 5.75% of transport fuels are supposed to arise from biofuels production. This target will be much harder to reach, since it necessitates changes in agricultural production patterns throughout the EU to grow the required amounts of biomass as an area of 16-40% of the arable farm land in the EU-15 countries would be needed to grow biofuel feedstock. Assessments of the biofuel potentials in the European countries indicate that the maximum share of arable land that can be used for growing biofuels feedstock in the entire EU is approximately 14% (Kavalov *et al*., 2003a, 2003b).

In the long run, the market share of biofuels is expected to increase even further. In this context, it is necessary for agricultural policy to internalize the external benefits of biofuels. Under current conditions, these benefits are not yet fully accounted for. In this assessment we will explore the economic and technical potentials of biofuels in Europe and their influence on agricultural food production. Using *EUFASOM*, the development of the agricultural sector is simulated until 2030 for various biofuel incentives and the resulting structures are compared to the current state of the bioenergy market. In the subsequent section, the model setup and the scenarios will be described. The results of the simulations are presented in section 3. These are discussed in section 4, where conclusions are drawn as well.

2 Methodology

So far, estimates of biofuel potentials in Europe are usually based on microeconomic assessments, where macroeconomic feedback is lacking. This study closes this gap by focusing on biofuel production in the context of the entire agriculture and forestry sector, paying attention to the close interdependencies between food and non-food agricultural production. This approach calls for the utilization of a model that endogenizes key processes of agricultural production in particular detail.

EUFASOM is a partial equilibrium model focusing on Europe that describes resource allocations for the agricultural and forestry sectors over a specified number of optimization periods. Land is allocated to maximize marginal profitability of all endogenous agricultural and forestry land uses (Schneider et al., 2008). The model output consists of equilibrium market prices of goods, yields and trade quantities of the goods covered in the model.

The European version of *FASOM* is based on an approach developed at Texas A&M University. The original version, which is suitable for the U.S. only, was particularly adapted to comply with the situation in Europe. This led to the development of *EUFASOM*. The main features and detailed descriptions of the main equations are given in Schneider et al. (2008).

This study applies the *EUFASOM* model in a way that it incorporates and combines empirical data on biofuel production and potentials (Henniges, 2007). Detailed data on current biofuel production, agricultural production, co-products of biodiesel and assumed biofuel capacities have been provided, as well as data on feedstock needs for bioethanol and production costs of biofuels. These data are integrated into the model for calibration purposes and for the assessment of the current situation.

The development of the biofuel market in Europe is simulated for the time period from 2000 to 2030. Calculations are performed in time steps of five years. It is assumed that a production target of 10 million hl of biofuels is reached by the end of the simulation period. During the simulations prices of commodities and market developments are endogenously determined. Simulations are conducted for various levels of economic incentives to produce biofuels in Europe. These scenarios will differ in the degree to which the production of biodiesel and ethanol is subsidized and whether the subsidies are applied directly to biofuel production or indirectly via the general costs of carbon emissions.

3 Results

Simulations with *EUFASOM* are conducted for a large range of biofuel incentives from no incentive to € 1000 per hl for illustrative purposes. It is rather unlikely that such high incentives for biofuel production are realized; however, such high price scenarios provide additional insights about the general model behavior and can be obtained at little additional cost. Economic and technical potentials are assessed, as well as the interdependency between agricultural biofuel and food production.

To explore the technical potential of biofuel production in Europe, the output from biofuel production is determined if biofuel production is maximized irrespective of the production costs and all suitable agricultural area is utilized for this purpose. For comparison, in 2003, fuel consumption for transportation in the 27 EU countries amounted to almost 1850 million hl of diesel and close to 1520 million hl of gasoline (IEA, 2006).

The technical potential of biodiesel production in Europe is slightly greater than 7000 million hl, while more than 10000 million hl could be produced if all of the agricultural land available in the EU would be used for this purpose (Fig. 1). The combined technical biofuel production potential is close to 16000 million hl. In this case each country has the choice, which biofuel is going to be produced. Consequently, the biofuel with the higher production efficiency is always selected.

In contrast to the technical potential, the economic potential considers production costs and opportunity costs of biofuel production (Fig. 1) and shows how resource scarcity limits the amount of biofuels that is feasible to be produced. For low combined production costs, there is a substantial expansion in biofuel production as biofuel prices can be maintained at reasonable levels. Considerable amounts of biofuels can be produced at prices below € 4 / l

(Fig. 2). Initially, biodiesel production is the more efficient choice as a limited amount of biodiesel can be produced at lower cost than bioethanol. Eventually, bioethanol production becomes more cost efficient than biodiesel production so that for large production targets bioethanol is relatively cheaper than biodiesel. However, it has to be noted that high production levels are possible only due to the concurrent subsidization by imports. The continued expansion of biofuel production leads to substantially higher prices, which puts a limit on the amount of biofuels produced in Europe. This limit is closer to the technical potential for biodiesel than for bioethanol.

Of course, higher levels of biofuel production have an influence on the amount and value of food crops grown in Europe. Figure 3 shows the indices of food crop prices, production, imports and exports in the EU25 countries as a function of the amount of biofuels produced. As biofuel production increases, less agricultural area can be allocated to the production of food crops. Consequently, agricultural food production decreases and has to be substituted by imports from other regions in the world. There is no saturation, as imports continue to rise with growing biofuel production targets. Overall consumption of agricultural commodities remains remarkably stable regardless of the biofuel production target and changes only very little. Of course, exports of agricultural commodities suffer considerably with increasing biofuel production since an increasing share of the goods produced is consumed or used industrially within Europe.

As the total agriculturally utilized area in Europe is unlikely to change significantly during the next few decades, it can be expected that the food crop production area develops complementarily to the area used for biofuel crop production. An assessment of the bioenergy production areas shows that the biofuel production target applied has a profound influence on the amount and distribution of agricultural land used for this purpose.

If no production target for biofuels is set in Europe, the amount of agricultural land used for growing crops that can be used for bioethanol production generally exceeds the area allocated for biodiesel crop production (Fig. 4). The largest share of agricultural land, on which crops for bioethanol production are grown, is found in the United Kingdom, where more than half of the area is used that way. The share of land used for this purpose in Central Europe is somewhat lower but still amounts to around 50%. The area of agricultural land used to grow crops for biodiesel production is much lower. Only in Hungary this share exceeds 25%. Other countries with fairly high amounts of land allotted to this purpose include Germany, France, Spain and the Czech Republic.

The picture changes distinctly if a production target of biofuels in introduced in Europe. For a target of 2000 million hl of biofuels the amount of land allocated to grow crops for bioethanol production expands greatly and shares of 50% are exceeded in practically all parts of Europe (Fig. 5). In addition to the United Kingdom, where this land allocation was already high to start with, more than 75% of the agricultural land are used for bioethanol feedstock crops in Belgium, Slovenia and Greece. Biodiesel production plays a lesser important role in Europe. This fuel is mainly produced in Germany, which has a high production efficiency of biodiesel and large areas, on which the rapeseed necessary can be grown.

If the biofuel production target is increased even further, the dominance of bioethanol over biodiesel becomes even more evident. All European countries except Finland allocate more than half of their agricultural area to the growth of crops that are used to produce bioethanol. In most countries the share exceeds 75%, the United Kingdom reaches almost 90% (Fig. 6). On the other hand, biodiesel production is even less important than with a production target half as large. In no European country more than a quarter of the agricultural land is used to grow biodiesel feedstock crops. This has to do with the fact that the relative production output of bioethanol per unit area is larger than that of biodiesel. And the larger the overall production target becomes, the more agricultural land has to be set aside to grow fuel crops. Consequently, it is necessary to maximize the amount of biofuel produced on the limited land area available. This results in an almost exclusive focus on the production of bioethanol from wheat and sugar beet at the expense of rapeseed and other oilseeds, which are mainly used in biodiesel production.

There is a distinct pattern of biofuel production in Europe depending on the production target that is set. Overall, the total area of agricultural land allocated to wheat production remains more or less constant at slightly above 20 million ha, regardless of the biofuel production target specified (Tab. 1). Any policy changes regarding the production targets have a much more profound influence on the other two key biofuel crops. For small biofuel production targets of up to little more than 1000 million hl, the main expansion in production area occurs for rapeseed, thus increasing the output of biodiesel. For any larger biofuel production targets it is better to focus on the production of bioethanol. In order to achieve the desired production goals it is therefore necessary to grow much larger amounts of the ingredients of this particular biofuel. Since the limiting factor in this case is sugar beet, it is mainly that crop whose production is especially intensified. For large production targets the area on which sugar beet is grown exceeds the area of wheat by more than a factor of two. It is optimal to focus on the production of this crop since any wheat missing for the production of biofuels can be more readily imported from other regions of the world.

4 Discussion and Conclusion

In this assessment, the partial equilibrium model *EUFASOM* is applied to investigate the potentials of biofuel production in Europe in the near future and to explore the influence of an expanded biofuel production on agricultural food production. This is done by determining the extent of bioenergy production for various production targets either of biodiesel, bioethanol or both biofuels together.

The simulations reveal that there is a shift in the general agricultural production depending on the production target of biofuels. For moderate production targets it is more efficient to produce biodiesel and therefore grow large amounts of rapeseed and other oilseeds such as sunflowers. This leads to an initial expansion of areas of rapeseed growth, particularly in Central Europe, e.g. in Germany. If, however, it is desired to produce very large amounts of biofuels, it is necessary to focus more on the production of bioethanol. Therefore, a massive expansion in the production of wheat and sugar beet, the main ingredients of bioethanol, can be observed. This expansion in growth of the bioethanol feedstock can be observed in all regions of Europe, led by the United Kingdom. A closer look at the distribution of the individual crops shows that it is particularly sugar beet production that is enhanced in Europe as it is much easier to import additional wheat from other regions of the world as necessary. In conjunction with an increase in biofuel production, the production of agricultural food commodities in Europe decreases, causing consumption to decrease as well in the long run. Interestingly, there is not such a sharp signal in the price index of food crops. This has to do with the fact that food crop availability remains at stable levels via larger imports from other regions of the world.

The assessment of the technical potential of biofuels indicates that the scarcity of the resources used in the production process puts an economic cap on the amount of biofuels that can produced at a level that is still far away from the technically possible amount. Then the marginal costs of biofuel production would increase by such a large extent that it would make no sense to continue approaching the technical potential by all means. But even if the amounts of biofuels produced in Europe remained even below the economic potential, already a considerable share of the diesel and gasoline from fossil sources used for transportation could be replaced by fuels from agricultural production.

It should be noted that the results obtained in these simulations are dependent on the boundary conditions to which they are calibrated. They can therefore point to interesting effects occurring as a consequence of increases in biofuel production targets in Europe. However, this also means that the findings are only valid in the context of the settings that govern the simulations. All empirically obtained input data are subject to inherent uncertainty, which is transferred into the model. Possible changes in European energy policy or technical progress concerning biofuel production can have a profound influence on the efficiency of incentives to produce biofuels. The exploration of such developments is beyond the scope of this paper and would have to be conducted in a separate study.

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References

Azar, C. (2005): Emerging scarcities – Bioenergy-food competition in a carbon constrained world, in: Simpson, R.D., Toman, M.A. and Ayers, R.U. (eds.), *Scarcity and growth revisited, resources for the future*, RFF, Washington, DC, XX pp.

Commission of the European Communities (EU Commission) (2006): *An EU Strategy for Biofuels*, Report SEC (2006) 142, 29 pp.

Commission of the European Communities (EU Commission) (2007a): *An energy policy for Europe*, Report SEC (2007) 12, 28 pp.

Commission of the European Communities (EU Commission) (2007b): *Biofuels Progress Report – Report on the progress made in the use of biofuels and other renewable fuels in the Member States of the European Union*, Report SEC (2006) 1721, 28 pp.

Fernside, P.M. (1999): Plantation forestry in Brazil: the potential impacts of climatic change, *Biomass and Bioenergy*, **16**, 91-102.

Henniges, O. (2007): Die Bioethanolproduktion – Wettbewerbsfähigkeit in Deutschland unter Berücksichtigung der internationalen Konkurrenz. EUL-Verlag, Troisdorf, Germany, 2nd ed., 306 pp.

Hoogwijk, M., Faaij, A., van den Broeck, R., Berndes, G., Gielen, D. and Turkenberg, W. (2003): Exploration of the ranges of the global potential of biomass for energy, *Biomass and Bioenergy*, **25**, 119-133.

Ignaciuk, A., Vöhringer, F., Ruijs, A. and van Ierland, E.C. (2006): Competition between biomass and food production in the presence of energy policies: a partial equilibrium analysis, *Energy Policy*, **34**, 1127-1138.

International Energy Agency (IEA) Statistics Division (2006): Energy Balances of OECD Countries (2006 edition) – Extended Balances. Paris, IEA. http://data.iea.org/ieastore/default.asp

Jerko, C. (1996): The economic potential of producing energy from agricultural biomass, MS thesis, Texas A&M University, College Station.

Johansson, D.J.A. and Azar, C. (2007): A scenario based analysis of land competition between food and bioenergy production in the US, *Climatic Change*, **82**, 267-291.

Kavalov, B. (2004): *Biofuel potentials in the EU*, European Commission Joint Research Center, Report EUR 21012 EN, 27 pp.

Kavalov, B., Jensen, P., Papageorgiou, D., Schwensen, C. and Olsson, J.P. (2003): *Biofuel Production Potential of EU-Candidate Countries – Final Report*, Report EUR 20835 EN 2003, 38 pp.

Kavalov, B., Jensen, P., Papageorgiou, D., Schwensen, C. and Olsson, J.P. (2003): *Biofuel Production Potential of EU-Candidate Countries – Addendum to the Final Report*, Report EUR 20836 EN 2003, 91 pp.

Kutas, G., Lindberg, C. and Steenblik, R. (2007): *Biofuels – at what cost? Government support for ethanol and biodiesel in the European Union*, Geneva, Switzerland, Global Subsidies Initiative of the International Institute for Sustainable Development, 46 pp.

McCarl, B.A., Adams, D.M., Alig, R.J. and Chmelik, J.T. (2000): Competitiveness of biomass-fueled electrical power plants, *Annals of Operations Research*, **94**, 37-55.

McCarl, B.A. and Schneider, U.A. (2000): U.S. Agriculture's role in a greenhouse gas mitigation world: an economic perspective, *Review of Agricultural Economics*, **22**, 134-159.

McCarl, B.A. and Schneider, U.A. (2001): Greenhouse gas mitigation in U.S. agriculture and forestry, *Science*, **294**, 2481-2482.

Schneider, U.A. and McCarl, B.A. (2003): Economic potential of biomass based fuels for greenhouse gas emission mitigation, *Environmental and Resource Economics*, **24**, 291-312.

Schneider, U.A., Balkovic, J., DeCara, S., Franklin, O., Fritz, S., Havlik, P., Huck, I., Jantke, K., Kallio, A.M.I., Kraxner, F., Moiseyev, A., Obersteiner, M., Ramos, C.I., Schleupner, C., Schmid, E., Schwab, D. and Skalsky, R. (2008): *The European Forest and Agricultural Sector Optimization Model – EUFASOM*, Research Unit Sustainability and Global Change, Working Paper FNU-156, Hamburg, Germany.

Solberg, B., Dornburg, V., Bolkesjø, T.F., Faaij, A., Junginger, M. and Trømberg, E. (2007): *Bioenergy and biomass trade: Evaluation of models' suitability for analyzing international trade of biomass and bioenergy products*, IEA Bioenergy Task 40, Aas and Utrecht, Netherlands, 42 pp.

Table 1. Area used to grow biofuel crops (in million ha) for different production targets

	wheat	sugar beet	rapeseed
no target	22.71	16.83	3.38
400	22.65	17.03	7.81
800	22.55	16.46	15.49
1200	21.69	21.54	13.71
1600	20.46	26.36	12.96
2000	20.69	33.17	8.13
2400	22.01	38.94	3.50
2800	21.23	43.00	3.54
3200	21.30	46.54	3.57
3600	21.50	49.71	3.57
4000	21.72	53.02	3.57

Figure 1. Economic versus technical potential of biofuel production in EU 25

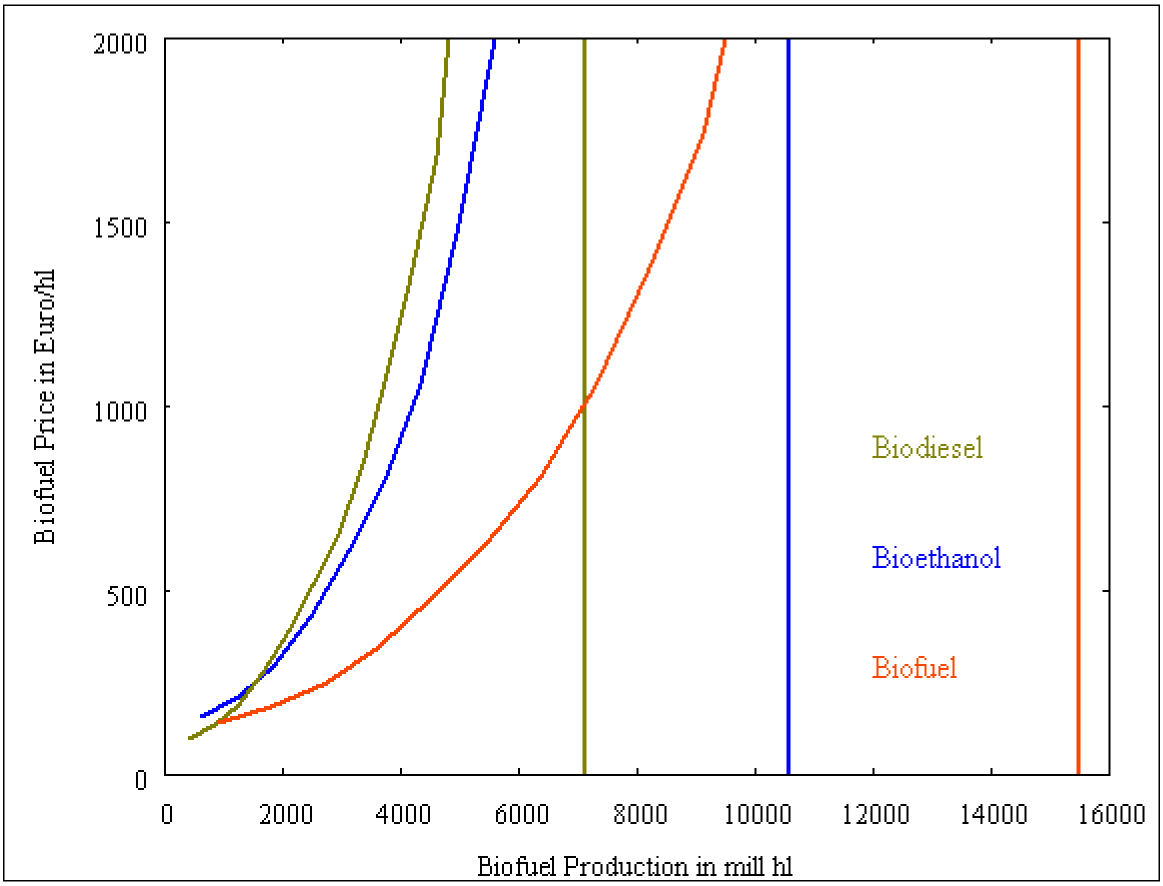


Figure 2. Supply function for bioethanol, biodiesel, or biofuels

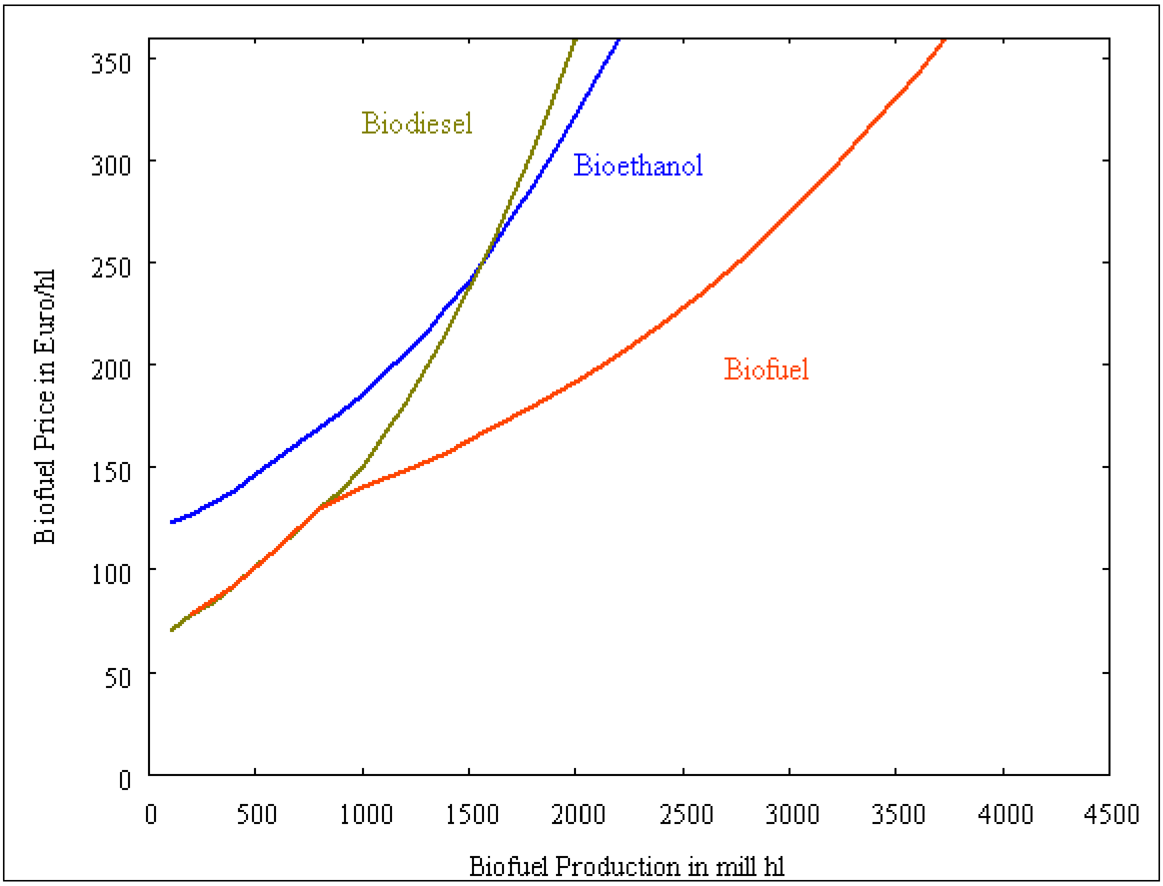


Figure 3. Impact of the biofuel target (bioethanol or biodiesel) on production, trade, and prices for agricultural commodities in EU 25.

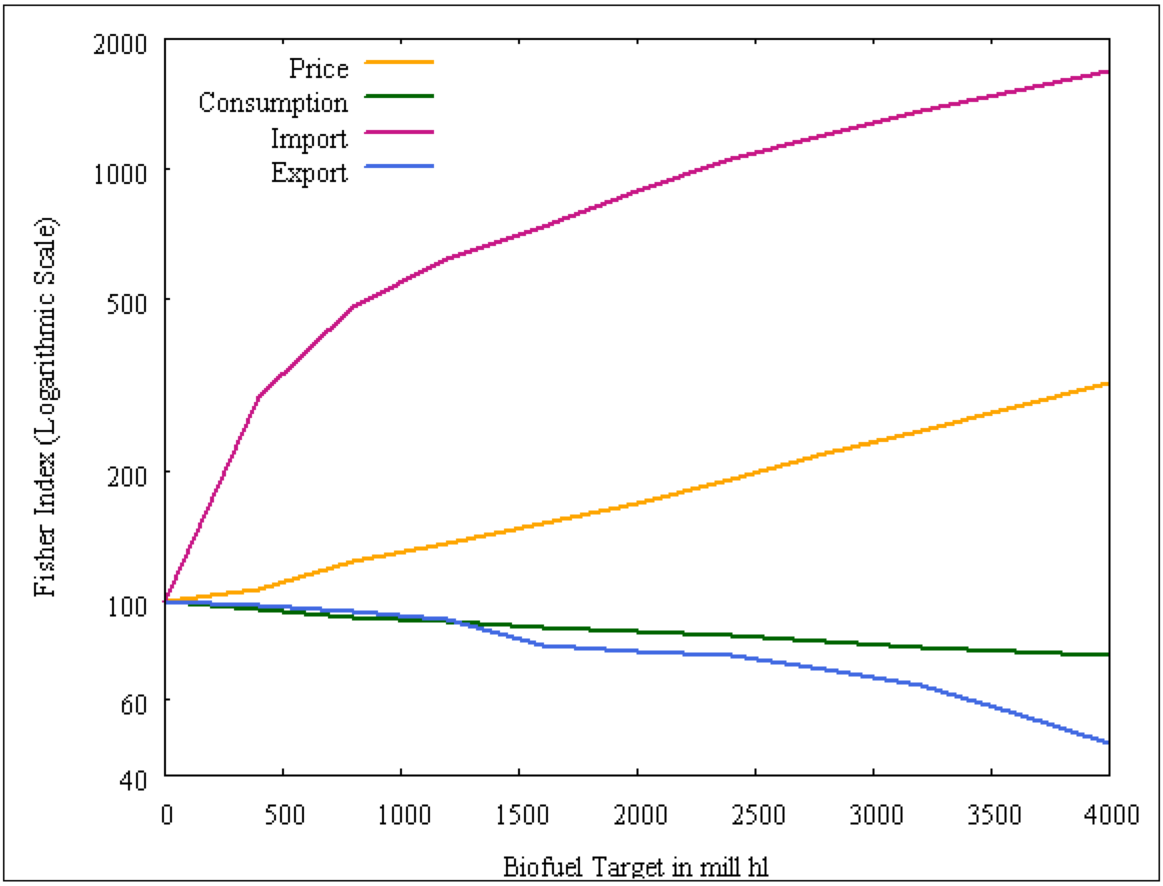


Figure 4. Shares of agricultural land area used for energy crop production for no biofuel production target.

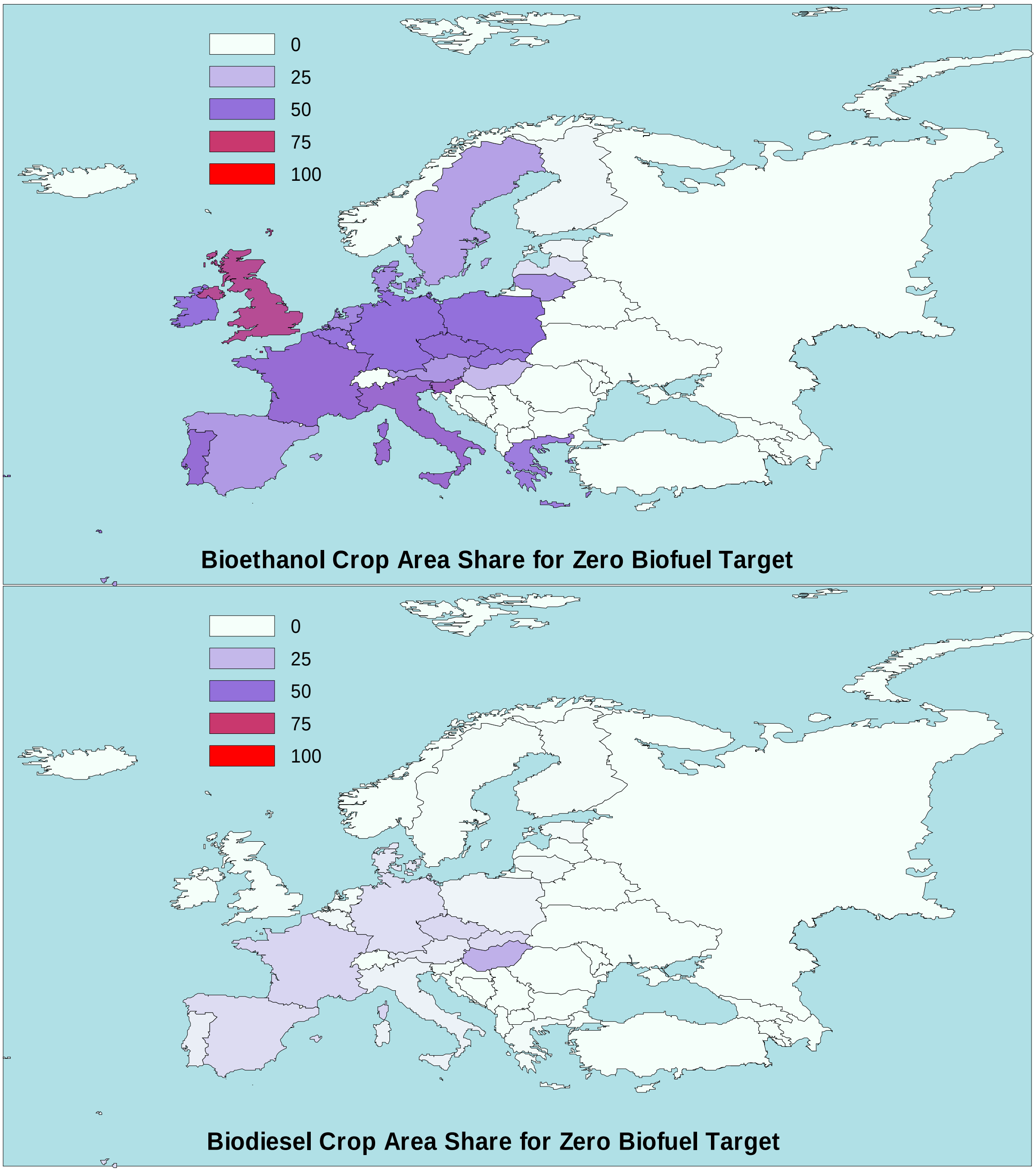


Figure 5. Shares of agricultural land area used for energy crop production for a biofuel production target of 2000 million hl.

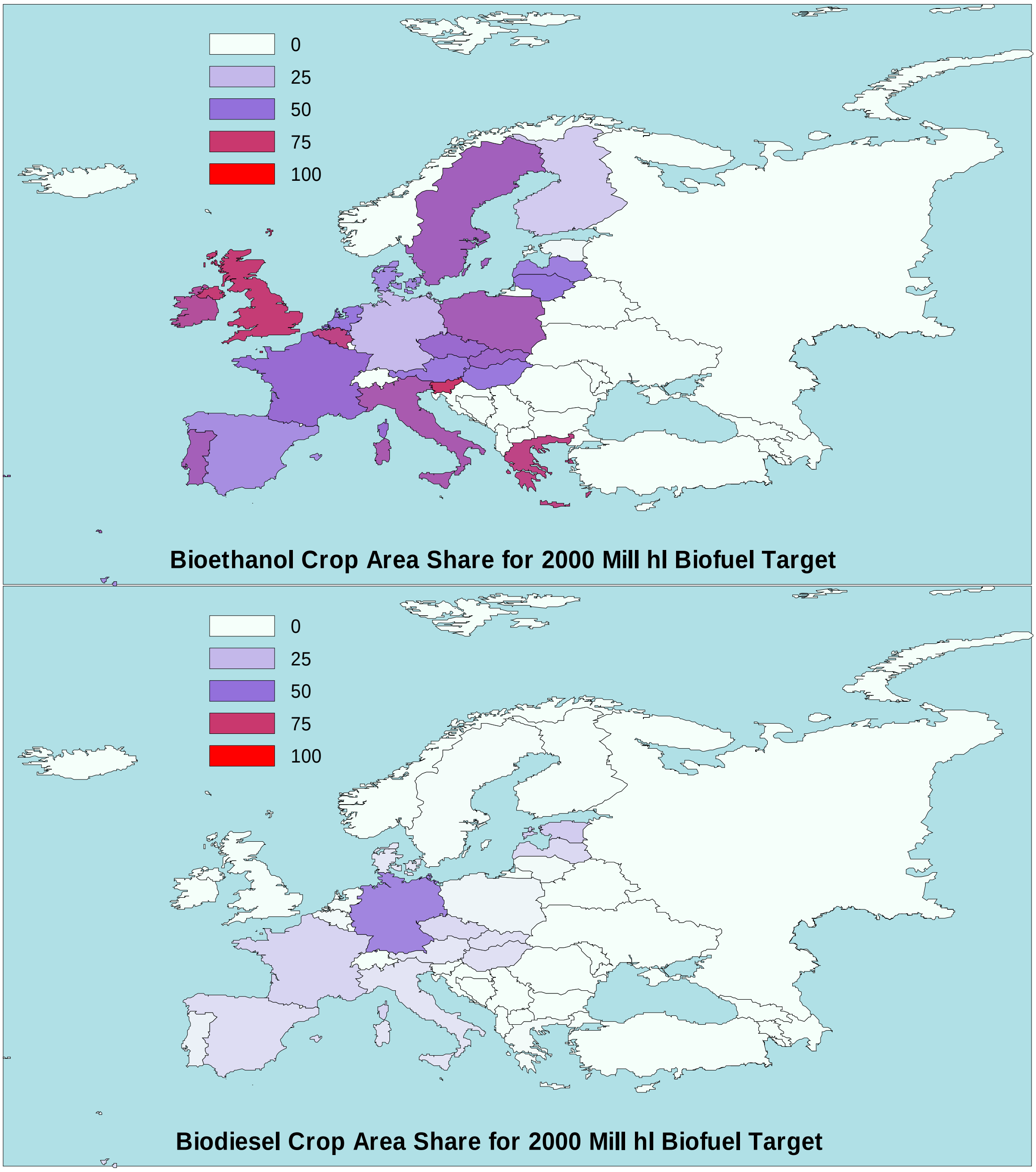
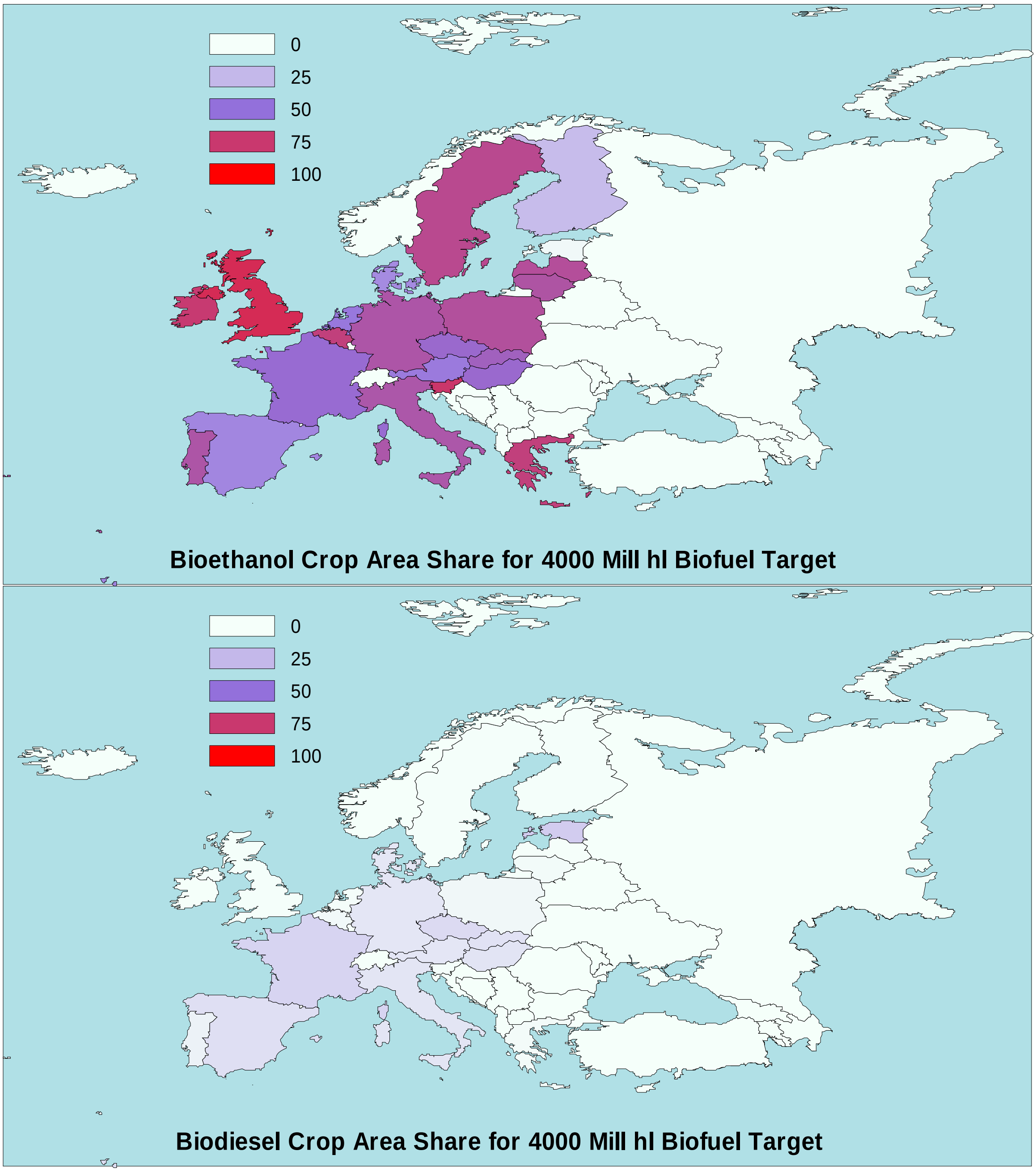


Figure 6. Shares of agricultural land area used for energy crop production for a biofuel production target of 4000 million hl.



Agriculture, population, and resource availability in a changing world – the role of irrigation water use for integrated large-scale assessments

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Abstract

Fertile land and fresh water constitute two of the most fundamental resources for food production. These resources are affected by environmental, political, economic, and technical developments. Regional impacts may transmit to the world through increased trade. With a global forest and agricultural sector model, we quantify the impacts of increased demand for food due to population growth and economic development on potential land and water use. In particular, we investigate producer adaptation regarding crop and irrigation choice, agricultural market adjustments, and changes in the values of land and water. Against the background of resource sustainability and food security topics, this study integrates the spatial and operational heterogeneity of irrigation management into a global land use model. To our knowledge this is the first large scale assessment of agricultural water use under consideration of alternative irrigation options in their particular biophysical, economic, and technical context, accounting for international trade, motivation-based farming, and quantified aggregated impacts on land scarcity, water scarcity, and food supply.

Keywords:

Irrigation methods, Water use intensity, Land scarcity, Agricultural adaptation, Food security, Partial equilibrium model

1. Introduction

Global population is projected to grow by about 65% within the next 50 years. At the same time, average per capita income is also expected to rise (Wallace, 2000). Together, these two developments imply a substantial increase in demand for water and food – not only because of more people, but also because of trends towards more water-intense lifestyles and diets. Water resources are an important economic driver because they constrain food production, energy generation, and activities in other economic sectors. The complex interdependencies between water resources and food production have been referred to in recent studies as an evolving global food crisis (Hightower and Pierce, 2008; Lundqvist et al., 2008).

The future supply of food and water faces several challenges. First, technical progress in agriculture may be subject to decreasing rates because of biophysical limits (Beadle and Long, 1985; Bugbee and Salisbury, 1988). Second, future land expansion may be restricted because of physical limits and conflicting demands. Furthermore, the productivity of existing cropland may decline because of soil degradation and expansion of other sectors on fertile agricultural land (Foley et al., 2005; Ramankutty et al., 2002). Third, environmental and human health regulations may constrain agricultural management and put limits to intensification (Rockstroem et al., 2004; Tilman et al., 2001; Van Hofwegen, 2006). Fourth, continued growth in domestic and industrial sector water consumption will decrease the available water volume for agriculture (Bouwer, 2000; Rosegrant et al., 2002). Fifth, if climate change intensifies, the productivity of agricultural systems will be impacted. These impacts will differ across locations and involve both improvements and deteriorations (Lobell et al., 2008; Milly et al., 2008; Ramankutty et al., 2002). While the above mentioned challenges may differ locally, their net impact is likely to affect all countries as agricultural commodities are heavily traded.

The global dimension of agricultural water use is evident from the fact that agriculture accounts for more than 70% of anthropogenic water withdrawals. Furthermore, about

20% of total arable cropland is under irrigation, producing 40% of the global harvest (Bruinsma, 2003). With continuing population growth and limited potential to increase suitable cropland, irrigation becomes an increasingly important tool to ensure sufficient global supply of food in the future (Wichelns and Oster, 2006).

Increasing levels of irrigation will increase the cost of water and in some regions this may cause severe problems of water scarcity. As water scarcity increases, inefficient allocation of water causes increasing costs to society. Missing property rights and inadequate water pricing are major causes of such inefficiencies. The magnitude of water-related externalities may further increase as international agreements to mitigate global change put more restrictions on agriculture or land use in general. Preventing these externalities from growing out of proportion is therefore in societies' best interest. However, national and international policymakers need scientific guidance to adequately regulate agricultural water use. In particular, appropriate assessments of agricultural water use need to consider a) the heterogeneity of natural and farming conditions, b) international commodity markets especially for agricultural products, c) agricultural and land use related environmental policies, and d) synergies and tradeoffs between different land use related externalities (Khan et al., 2008; Cowie et al., 2007).

In this study we investigate global interactions between future demand-based agricultural production and the availability of land and water resources, focusing irrigation as the major tool and determinant to affect both, agricultural productivity and environmental resource use.

Regarding existing literature on agricultural water use many studies that endogenously consider the adoption of irrigation practices stay at farm or basin scales. A few global assessments of irrigation distribution and impacts exist but mainly within disciplinary boundaries, i.e. physical geography or economics. These studies, however, do not account for site-specific differences between alternative irrigation systems and usually reduce and simplify decisions to a choice between rainfed and irrigated agriculture. Global integrated land use models accounting for multi-sectoral competition and limitations of land and water resources are rare (Heistermann et al., 2006).

We present a first attempt to integrate crop and site-specific irrigation methods into a global partial equilibrium model for the land use sectors. We analyse quantitatively how irrigation decisions respond to different development scenarios. Irrigation concerns are depicted by biophysically constrained and economically motivated decision options between alternative irrigation systems, each representing individual technical, environmental, and economic characteristics. This comprehends the explicit consideration of water and energy use efficiency as well as total irrigation costs.

Possible irrigation techniques in our model include four major systems in addition to rainfed agriculture. The suitability of these systems depends on various interdisciplinary factors, which influence crop suitability, water demand, energy requirement, labour intensity, and overall cost of irrigated agriculture, and thus affect motivation-based decision making that aims at individual or societal welfare maximization (Buchanan and Cross, 2002).

The model enables an integrated assessment of global agricultural land and water use, and the interrelations with subordinate-scale irrigation management, accounting for resource economics, commodity markets and international trade. Analyses explicitly consider regional capacities of irrigation system applicability, performance, and distribution based on respective geographic constraints and crop requirements.

Model output can be used to assess the impacts of political, technical, environmental, and market developments on agricultural management decisions and their aggregated impacts on scarcity of land and water, agricultural commodity supply and prices, and environmental externalities. Externalities may include deforestation, greenhouse gas emissions, soil erosion, and nutrient leaching.

2. Materials and Methods

Our paper is structured as follows. We portray the model and basic components of the irrigation module, followed by a more detailed description of the determinants of irrigation choice (crop profitability, resource endowments, water demand, energy demand, labour demand). For each of these elements we describe the methods used to derive parameter values, and the assumptions made on how the depicted elements are constituted and interlinked. Next we briefly explain the computation of total irrigation costs, depending on the particular biophysical and economic environment. Then we introduce the baseline scenarios and discuss first model results.

2.1 Global Forest and Agricultural Sector Model

We apply a mathematical programming-based, price-endogenous sector model of the agricultural and forestry sectors. The model depicts production, consumption, and international trade in 11 world regions (see Table 1). It was programmed using GAMS software (General Algebraic Modeling System).

Table 1 – Model world regions

The agricultural sector is represented by more than 40 crops, and an aggregated livestock sector. For crop management, the model can choose between different irrigation systems as described in detail in the following sections. Livestock production and consumption is represented by an aggregate of animal calories and is connected to crop production through fixed feed ratios. Except for the irrigation-related parameters the agricultural part of the model relies on FAO statistics accessible at http://faostat.fao.org. Forestry sector focuses on biomass production for sawnwood and wood pulp and represents also the first transformation level. It is an adapted version of the 4DSM model (Rametsteiner et al., 2007). The model also contains several bioenergy processing technologies and a complete greenhouse gas accounting, but those are not the focus of the present analysis.

The model simulates the market and trade equilibrium in global agricultural markets. The market equilibrium reveals commodity and factor prices, levels of domestic production, export and import quantities, resource usage, and environmental impacts.

2.2 Irrigation Module

Four irrigation methods are portrayed: surface irrigation systems including basin and furrow irrigation, localised drip irrigation, and sprinkler irrigation (represented by center-pivot sprinklers). Current cost trends of water delivery infrastructures made us assume piped water delivery from the source to the field for all of the systems (Phocaides, 2000). For each method we evaluate biophysical and technical compatibility to exclude inappropriate irrigation decisions. The final choice of crop and management type is motivated by profit maximisation subject to resource constraints. Profitability is defined as revenue less production costs. Crop revenue is calculated as the expected yield per spatial unit times the respective market price per unit of yield. Production costs contain all expenses for management and inputs required to reach the respective management-related yield. The interdisciplinary range of factors that determine irrigation decisions in our model is shown in Table 2.

Table 2 – Biophysical, technical, and economic determinants of irrigation choice

Crop yields and corresponding irrigation demands are based on exogenous databases (FAO, 2004 and 2007; Skalsky et al., 2007). Yearly water availability for irrigation considers internal renewable water resources less water requirements of other sectors (FAO Land and Water Development division, 2008). Land resources are further classified by slope and soil type (Skalsky et al., 2007) (Table 3).

Table 3 – Classifications for slope inclination and soil texture

We also considered system application efficiencies to project gross water demands. Actual water use is finally computed considering irrigation cost per spatial unit for all appropriate combinations of regional geographic background, crop type, and irrigation system. Specific irrigation system characteristics including water application efficiency are portrayed in Table 4.

Table 4 – Specific characteristics of the different irrigation systems

2.3 Parameterisation: Energy Requirement

Four energy sources can be used optionally: Electricity, diesel, gasoline, and natural gas. Energy use is a function of irrigated area, water demand, pressure requirement, and total irrigation time (Buchanan and Cross, 2002). Pressure for pumping is determined by estimated pipe length and lifting height.

On-farm irrigation scheduling is affected by various functional relationships among geographic and technical parameters (compare Table 2 in chapter 2.2). We used a simplified but consistent approach to represent these interdependencies by means of 'generalised irrigation scheduling'. In this context 'application depth per irrigation event' is an important parameter to calculate cost-effective energy demand. We used a stepwise approach to determine application depth based on the assumption of fixed operation times per irrigation event (Table 5).

Table 5 – Assumed fixed operation times per irrigation event

The schedules assume uniform application depths during complete vegetation period. Guide values on soil infiltration rate, suitable slope, the acceptable range of flow rate by soil type at optimal slope, and corresponding size of irrigated area were taken from Brouwer et al. (1988).

In a first step we calculated maximum number of events with respect to length of growing period (Fischer et al., 2002) and common application frequencies (Brouwer et al., 1988; Buchanan and Cross, 2002). Using the total irrigation water demand over the complete vegetation period, we accordingly determined application depth per event by country, crop, and method.

Second, we calculated maximum application depth by soil type at optimal slopes with respect to recommended flow rates and particular soil infiltration rates (Brouwer et al., 1988).

To account for slope effects on surface irrigation performance we modified the application depths for basin irrigation using ratios between recommended and minimum flow rate as multipliers, while assuming proportionality of irrigation depth and flow rate. Then we derived ‘slope-related basin size factors’, which depict the maximum basin area by slope class in percent of the optimum-slope basin area when flow rate is the same (see Table 6). For this we assumed quadratic basins and a linear relationship between slope and basin size. These slope coefficients were applied to previous soil-indexed optimal-slope application depths.

Table 6 – Basin irrigation: Derived coefficients for the adjustment of ‘optimal-slope application depth’ to higher slope classes, to account for relationships between slope inclination, tolerable soil-dependent flow rates, and maximum basin-irrigated area

Regarding furrow irrigation, we considered soil and slope influences on maximal furrow length and their implications for acceptable flow rate according to approx values given by Brouwer et al. (1988). We transformed furrow lengths to ‘area per furrow’ and determined application depth per furrow (by country, crop, soil type, and slope) for maximal area under consideration of operation time:

$$AD_{slope,\ soil} = OT * FR\ max_{slope} / A\ max_{slope,\ soil}$$

$AD_{slope,\ soil}$:	Application depth per irrigation event for furrow irrigation [mm] by slope class and soil type
OT:	Operation time per irrigation event for furrow irrigation [sec]
$FR\ max_{slope}$:	Maximum flow rate per furrow [l/sec] by slope class
$A\ max_{slope,\ soil}$:	Maximum area per furrow [m²] by slope class and soil type

After modifying the surface application depths we re-calculated yearly numbers of irrigation events based on total water requirements, and determined the 'final' application depth per event.

Energy use for irrigation is determined by underlying pressure requirements. Total pressure requirement is the sum of sprayer pressure (for non-surface systems) and static head pressure to bridge elevation differences. Information on sprayer pressure and static head pressure calculation were obtained from Buchanan and Cross (2002) and USDA-NRCS (2007).

2.4 Parameterisation: Labour Requirement

Labour requirement is the number of irrigation events times estimated labour hours per event as taken from Turner and Anderson (1980; cited in Buchanan and Cross, 2002) (Table 7).

Table 7 – Estimated labour hours per acre and irrigation event

To depict variations by crop type we introduced a ‘crop labour factor’ as a multiplier (Table 8), based on costs per spatial unit (AgEBB, 2006; Paul, 1997), and used the value of maize as benchmark.

Table 8 – Crop labour factor by crop type and irrigation method

2.5 Irrigation Cost

Irrigation costs include capital costs and costs for operation and maintenance (O&M). Operation costs are composed of pressure-related energy costs in terms of energy prices by source (EIA, 2006; Metschies, 2005), and labour costs in terms of average agricultural wages per hour (IMF, 2007; World Bank, 2006). For unavailable yearly items we inter- or extrapolated mean trends. For a schematic overview on the determination of total irrigation costs see Fig. 1.

Fig. 1 – Scheme for determining total irrigation costs

At present stage, capital and maintenance costs by method were assumed to be globally identical despite the fact that they may substantially differ between regions (Rosegrant et al., 2002).We took capital costs per spatial unit for center-pivot sprinklers as reference (Reinbott, 2005) to determine costs of drip and surface systems, using further technical information on these systems by Phocaides (2000). Maintenance cost was set to 5% of capital cost for non-surface and furrow irrigation, and to 3% for basin irrigation (Phocaides, 2000; Paul, 1997).

3. Baseline Scenarios

Population growth affects agriculture through increased demand for food. Higher demand for land and water from non-agricultural sectors increases the scarcity of these two resources. Economic development may additionally affect food demand qualitatively and quantitatively via shifts in consumption patterns and increasing demand for water-intense commodities.

We analyse these drivers independently and jointly on a resolution of 11 world regions (see Table 1 in chapter 2.1), which contain a total of 203 individual countries or subregions, respectively.

Increase of population from 2000 to 2030, according to the IIASA GGI A2r baseline scenario calculations, portrays the major driving force for scenario simulation (IIASA, 2008). We estimated future food demand by multiplying regional projections of per capita calorie intake (Alexandratos et al., 2006) with the increment in regional population according to the GGI scenarios.

The average daily calorie intake per head is projected to increase in all regions. Highest rates are assumed for regions that are also predicted to have high population growth (Sub-Saharan Africa, most Asian countries). In regions with increasing rates of economic development, expected dietary shifts are represented by a growing fraction of livestock products among the daily calorie intake.

Supplementary pressure from population growth in terms of increased residential water and land demand, causing reductions in water and land available for agriculture, was calculated using domestic water consumption (FAO Land and Water Development Division, 2008), and population density data (Demographia, 2006). We assumed that residential land growth takes the form of urban expansion.

Baseline reference data on land and water endowments, and on irrigation distribution (Table 9) was obtained from FAOSTAT, AQUASTAT, and ICID databases (FAO 2000, 2004, and 2007; FAO Land and Water Development Division, 2008; ICID, 2008).

Table 9 – Baseline irrigation system distribution by region

4. Results and Discussion

We will describe simulated trends of irrigated area and water use intensity to analyse these results in the context of alternative irrigation options.

Rising demands for food lead to increasing crop, land, and water prices. Water supply functions with constant elasticity were applied. Technological progress affecting productivity is not considered in the model runs.

The resulting water price indices are presented for selected regions in Fig. 2.

Fig. 2 – Results: Water price index by region

Total water use is going to increase at only slightly varying rates until about 80% of the total population increase projected until 2030 has proceeded. From this point, increase rates decline accompanied by corresponding price increases for water (Fig. 3).

Fig. 3 – Results: Global irrigation water use

Simulations indicate highest increase and totals of irrigated area in South Asia (SAS). Increasing rates of irrigated area expansion are also predicted for Latin America and the Caribbean (LAM), Former Soviet Union (FSU), Planned Asia with China (CPA), and Other Pacific Asian states (PAS). After a relatively long period of population growth a stronger expansion of irrigated area is finally also simulated for Sub-Saharan Africa (AFR). The global trend of irrigated land expansion is depicted in Fig. 4.

Fig. 4 – Results: Global irrigated land

Global water use intensity more or less continuously decreases over time (see Fig. 5). Whereas water intensity remains constant in CPA and LAM, it substantially decreases in Africa and – to a lesser extent – in SAS, despite high rates of population growth and high increases of per-capita calorie intake. Globally, a general trend of combined expansion and extensification of irrigated agriculture can be identified.
Critical thresholds to trigger explicit shifts in regional irrigation management towards improved water use efficiency seem to appear when about 60-80% of predicted global population growth has taken place. In between 20-60% of total population growth, water use efficiency improvement is progressing at comparably low rates.

Fig. 5 – Results: Global agricultural water use intensity

We will face a general trend of irrigated area expansion to sufficiently meet changing food demands. Additional water and land pressure due to residential demands accelerate the increase in irrigated area, but simultaneously trigger an extensification of management practises in terms of decreasing water use intensity.

Residential pressure on land resources seems to force shifts from rainfed to irrigated agriculture to maintain food production, whereas residential pressure on water resources restricts water intensity when water becomes scarce, and consequently approves water-efficient irrigation methods or, respectively crop types with lower irrigation demands.

Food demand-induced needs for irrigation expansion may be met by more water-efficient irrigation methods: Results show that after some time 'current' and additional agricultural production likely shifts to more water saving irrigation practices (see Fig. 6 for global trends). On long-term a broad application of relatively expensive but most water-efficient methods is eventually triggered. On global scale, a progressive substitution of sprinkler irrigation by drip systems appears first, before eventually also surface irrigation decreases in favor of water-efficient pressurised techniques.

In higher developed regions such 'shifting trends' appear earlier and more smoothly than in less developed regions. Besides technological standards, cost recovery for investment and O&M may play a major role.

Fig. 6 – Results: Irrigation methods (global)

The timing of the occurrence of ‘global irrigation shifts’ can be illustrated by simulated global developments of surface irrigation. A global dominance of surface methods (especially basin irrigation), which is predicted for the early stages of population development, is likely related to the specific characteristics of rice production, in conjunction with regional population dynamics: As long as water supply is not a limiting factor to irrigation decisions, basin irrigation can be maintained at high levels and further increased as the market price of rice is relatively high, basin irrigation is cheap, and food demand grows. But particularly regions most suitable for rice cultivation also have high rates of population growth (e.g., SAS, CPA), and thus are particularly exposed to occurring problems of water scarcity. A shift away from the combination of high water demands, large areas, and water-inefficient irrigation performance leads to considerable water savings per hectare.

5. Conclusions

We developed a modelling framework to globally quantify regional adaptations of agricultural water use to development scenarios under explicit consideration of operational heterogeneity, resource efficiency, and related economic issues of alternative irrigation options. The integration into a partial equilibrium model for land use sectors represents a new approach to assess global land use changes by exploring synergies and trade-offs between future food production and environmental externalities with an emphasis on problems of increasing scarcity of land and water resources. The model is applicable to evaluate interdependencies between socioeconomic development and policies on one side and land use related externalities, resource availability, and food supply on the other side. Our simulations show that agricultural responses to population and income growth include considerable increases in irrigated area and agricultural water use, but reductions in the average water use per irrigated hectare.

Irrigation is a complex decision beyond the binary decision of adopting irrigation or not. Different irrigation systems are preferred under different exogenous conditions including biophysical and socioeconomic factors. Negligence of these adaptations would bias the burden of development on land and water scarcity.

Without technical progress in agriculture, a population and income level as predicted under GGI A2r scenario for 2030 would require substantial price adjustments for land, water, and food to equilibrate supply and demand.

To accurately estimate land and water scarcity, the likely adaptation of farmers to different irrigation methods needs to be quantified. In particular, we excluded from this analysis institutional and other barriers to adopt more advanced irrigation technologies. Furthermore, this work needs to be complemented by more detailed hydrological studies on the physical availability of green and blue water supply.

The study underlines the need for integrated approaches to assess the role of water resources and irrigation in the context of future food security and overall socioeconomic welfare. The inclusion of technical and economic aspects of irrigation choice can provide new insights into the interdisciplinary trade-offs between determinants of global land use change. To conclude, let us state that the present paper represents only the very beginning of our analysis and the model is being continuously improved so that new, maybe more accurate results can be presented soon.

Acknowledgements

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References

AgEBB (Agricultural Electronic Bulletin Board, Missouri), 2006. SEMO Crop Budget 2006. Missouri Irrigation Economics (University of Missouri Extension Southeast Missouri). Missouri. (http://agebb.missouri.edu/irrigate/economics/ index.htm).

Alexandratos, N., Bruinsma, J., Bödeker, G., Schmidhuber, J., Broca, S., Shetty, B., Ottaviani, M.G. (Eds.), 2006. World agriculture: towards 2030/2050 - Prospects for food, nutrition, agriculture and major commodity groups. FAO, Global Perspective Studies Unit, Rome.

Beadle, C.L., Long, S.P., 1985. Photosynthesis - is it limiting to biomass production? Biomass 8, 119-168.

Bouwer, H., 2000. Integrated water management: emerging Issues and challenges. Agricultural Water Management 45, 217–228.

Brouwer, C., Prins, K., Kay, M., Heibloem, M., 1988. Irrigation Water Management: Irrigation Methods. FAO Irrigation Water Management Training manual no 5.

Bruinsma, J. (Ed.), 2003. World agriculture: towards 2015/2030 – An FAO Perspective. FAO, Rome, and Earthscan Publications Ltd, London.

Buchanan, J.R., Cross, T.L. (Eds.), 2002. Irrigation Cost Analysis Handbook. Agricultural Extension Service, The University of Tennessee, PB1721.

Bugbee, B.G., Salisbury, F.B., 1988. Exploring the Limits of Crop Productivity : I. Photosynthetic Efficiency of Wheat in High Irradiance Environments. Plant Physiology 88, 869-878.

Cowie, A., Schneider, U.A., Montanarella, L., 2007. Potential synergies between existing multilateral environmental agreements in the implementation of land use, land-use change and forestry activities. Environmental Science & Policy 10, 335-352.

Demographia, 2006. World Urban Population Density by Country & Area. (http://www.demographia.com/db-intlua-area2000.htm).

EIA (Energy Information Administration), 2006. International Energy Annual (IEA) 2004 – long-term historical international energy statistics. Official Energy Statistics from the U.S. Government. (http://www.eia.doe.gov/iea/).

FAO, 2000. FAOSTAT 2000 (FAO Statistical Databases).

FAO, 2004. FAOSTAT 2004 (FAO Statistical Databases).

FAO, 2007. FAOSTAT online database. (http://www.fao.org).

FAO Land and Water Development Division, 2008. AQUASTAT information system on water and agriculture. (http://www.fao.org/ag/agl/aglw/aquastat/main/index.stm).

Fischer, G., van Velthuizen, H., Shah, M., Nachtergaele, F., 2002. Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results. International Institute for Applied Systems Analysis, Laxenburg, Austria, & FAO, Rome.

Foley, J.A., De Fries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global Consequences of Land Use. Science 309, 570–574.

Heistermann, M., Müller, C., Ronneberger, K., 2006. Land in Sight? Achievements, Deficits and Potentials of Continental to Global Scale Land-Use Modeling. Agriculture Ecosystems and Environment 114 (2-4), 141–158.

Hightower, M., Pierce, S.A., 2008. The energy challenge. Nature 452, 285–286.

ICID (International Commission on Irrigation and Drainage), 2008. ICID Database. (http://www.icid.org/).

IIASA (International Institute for Applied System Analysis), 2008. GGI Scenario Database. (http://www.iiasa.ac.at/Research/GGI/DB/)

IMF (International Monetary Fund), 2007. World Economic Outlook Database, April 2007 Edition. (http://imf.org/external/pubs/ft/weo/2007/01/data/ index.aspx).

Khan, S., Abbas, A., Gabriel, H.F., Rana, T., Robinson, T., 2007. Hydrologic and economic evaluation of water-saving options in irrigation systems. Irrigation and Drainage 57, 1–14.

Lobell, D.B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P., Naylor, R.L., 2008. Prioritizing Climate Change Adaptation Needs for Food Security in 2030. Science 319, 607–610.

Lundqvist, J., De Fraiture, C., Molden, D., Berndes, G., Berntell, A., Falkenmark, M., Holmen, H., Karlberg, L., Lannerstad, M., 2008. Saving Water: From Field to Fork – Curbing Losses and Wastage in the Food Chain (Draft for CSD, May 2008). SIWI Paper 13. Stockholm International Water Institute.

Metschies, G.P. (Ed.), 2005. International Fuel Prices 2005 (4th Edition - 172 Countries). Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) / Federal Ministry for Technical Cooperation and Development, Germany (BMZ).

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J., 2008. Stationary is dead: Whither Water Management? Science 319, 573–574.

Paul, N. (Ed.), 1997. Irrigation Technology Transfer in Support of Food Security (Proceedings of a subregional workshop in Harare, Zimbabwe, 14-17 April 1997). FAO Water Reports – 14.

Phocaides, A. (Ed.), 2000. Technical Handbook on Pressurized Irrigation Techniques. FAO, Rome.

Ramankutty, N., Foley, J.A., Norman, J., McSweeney, K., 2002. The global distribution of cultivable lands: current patterns and sensitivity to possible climate change. Global Ecology & Biogeography 11, 377–392.

Rametsteiner, E., Nilsson, S., Boettcher, H., Havlik, P., Kraxner, F., Luc, S., Obersteiner, M., Rydzak, F., Schneider, U.A., Schwab, D., Willmore, L., 2007. Study of the Effects of Globalization on the Economic Viability of EU Forestry. Final Report of the AGRI Tender Project: AGRI-G4-2006-06. Report to the European Commission, International Institute for Applied Systems Analysis (IIASA). Laxenburg, Austria.

Reinbott, D., 2005. Irrigation Investment and Ownership Cost. Missouri Irrigation Economics (University of Missouri Extension Southeast Missouri), Agricultural Electronic Bulletin Board (AgEBB). Missouri. (http://agebb.missouri.edu/irrigate/economics/index.htm).

Rockstroem, J., Folke, C., Gordon, L., Hatibu, N., Jewitt, G., Penning de Vries, F., Rwehumbiza, F., Sally, H., Savenije, H., Schulze, R., 2004. A watershed approach to upgrade rainfed agriculture in water scarce regions through Water System Innovations: an integrated research initiative on water for food and rural livelihoods in balance with ecosystem functions. Physics and Chemistry of the Earth 29, 1109–1118.

Rosegrant, M.W., Cai, X., Cline, S.A., 2002. World Water and Food to 2025: Dealing with Scarcity. International Food Policy Research Institute, Washington D.C. Mimeo.

Skalsky, R., Schmid, E., Tarasovicova, Z., Balkovic, J., 2007. Detailed description of the data strategy for global EPIC modelling. GEO-BENE Data Base Report (D6), App.

Tilman, D., Fargione, J., Wolff, B., D´Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., Swackhamer, D., 2001. Forecasting agriculturally driven Global Environmental Change. Science 292, 281–284.

Turner, J.H., Anderson, C.L. (Eds.), 1980. Planning for an Irrigation System. American Association for Vocational Instructional Materials, Engineering Center, Athens, Georgia.

USDA-NRCS (U.S. Department of Agriculture, Natural Resources Conservation Service) 2007. Energy Consumption Awareness Tool: Irrigation. (http://ipat.sc.egov.usda.gov/Help.aspx).

Van Hofwegen, P., 2006. Task Force on Financing Water For All, Report 1: Enhancing access to finance for local governments - Financing water for agriculture. World Water Council, Marseille.

Wallace, J.S., 2000. Increasing agricultural water use efficiency to meet future food production. Agriculture, Ecosystems and Environment 82, 105–119.

Wichelns, D., Oster, J.D., 2006. Sustainable irrigation is necessary and achievable, but direct costs and environmental impacts can be substantial. Agricultural Water Management 86, 114–127.

World Bank, 2006. World Development Indicators 2006.

Table 1 - Model world regions (incl. abbreviations)
North America (NAM)
Western Europe (WEU)
Pacific OECD (PAO)
Central and East Europe w/o former SU (EEU)
Former Soviet Union (FSU)
Planned Asia with China (CPA)
South Asia (SAS)
Other Pacific Asia (PAS)
Middle East and North Africa (MEA)
Latin America and Caribbean (LAM)
Sub-Saharan Africa (AFR)

Table 2 - Biophysical, technical, and economic determinants of irrigation choice

Biophysical factors	Technical factors	Economic factors
Crop characteristics (water tolerance, rainfed and irrigated yields, irrigation demand)	Water application efficiency	Crop market prices
Soil infiltration rate	Operation time per irrigation event	Investment capital cost
Slope inclination	Level of pressurisation (energy and labour requirement)	Energy prices
Length of growing period	Coverage per irrigation system unit	Labour cost
Water resource availability		Land and water prices (resource economics)

Table 3 - Classifications for slope inclination and soil texture

Slope classes definition (intervals) (slope inclination in units of degree)	Soil classes definition
0 - 0.35	sandy
0.35 - 1	loamy
1 - 1.6	clay
1.6 - 2.25	stony
2.25 - 3	peat
3 - 6	
6 - 10	
10 - 15	
15 - 30	
30 - 50	
> 50	

Table 4 - Specific characteristics of different irrigation systems

	Basin	Furrow	Drip	Center Pivot
Functional type	Gravity	Gravity	Pressurised	Pressurised
Irrigation system category	Surface irrigation	Surface irrigation	Localised irrigation	Sprinkler irrigation
Capital cost	low	low	high	medium
Energy demand for operation	none	none	low	high
Maintenance and labour intensity	low	high	medium	medium
Water application efficiency at the field level (%)*	40	30	90	85
Notes	water-resistant crops, constrained by slope and soil	constrained by slope and soil	economically and technically unavailable to many farmers in developing countries	simple in application, convenient for large areas

*Values based on estimates by Buchanan and Cross (2002), and Phocaides (2000)

Table 5 - Assumed fixed operation times per irrigation event by irrigation method

Irrigation method	Estimated number of operation hours per irrigation event[*]
Basin irrigation	48
Furrow irrigation	48
Drip irrigation	48
Sprinkler irrigation	60

[*]Estimated guide values by Buchanan and Cross (2002)

Table 6 – Basin irrigation: Derived coefficients for the adjustment of ‘optimal-slope application depth’ to higher slope classes, to account for relationships between slope inclination, tolerable soil-dependent flow rates, and maximum basin-irrigated area

Slope class (intervals in units of degree)	'Basin-slope coefficient'*
0 - 0.35	0.875
0.35 - 1	0.092
1 - 1.6	0.013
1.6 - 2.25	0.006
> 2.25	not convenient for basin irrigation

*Estimates based on information by Brouwer et al. (1988)

Table 7 - Estimated labour hours per acre and irrigation event by irrigation method

Irrigation method	Estimates of labour required[*] (hours per acre per event)
Basin irrigation	0.5
Furrow irrigation	0.7
Drip irrigation	0.07
Sprinkler irrigation	0.1

[*]Values based on estimates by Turner and Anderson (1980)

Table 8 - Crop labour factor by crop type and irrigation method to account for crop-specific variations in labour required

Crop type	Crop labour factor by irrigation method[*]			
	Basin	Furrow	Drip	Sprinkler
Rice	2.3	2.3	1	4.2
Vegetables (all)	1	1.5	1	1
All other crops	1	1	1	1

[*]Estimates based on information by AgEBB (2006), and Paul (1997)

Table 9 - Baseline irrigation system distribution by region

World region	Assumed fraction of irrigation methods on total irrigated area (%)*		
	Basin and Furrow	Drip	Sprinkler
North America	47.48	6.59	45.93
Western Europe	33.97	17.95	48.08
Pacific OECD	79.71	5.04	15.25
Central and East Europe	38.50	2.62	58.88
Former Soviet Union	58.30	0.05	41.65
Planned Asia with China	97.00	1.00	2.00
South Asia	95.64	0.20	4.16
Other Pacific Asia	100	0	0
Middle East and North Africa	87.60	1.40	11.00
Latin America and Caribbean	86.66	2.50	10.84
Sub-Saharan Africa	69.51	4.73	25.76

*Estimates based on information by FAO (2000-2008), and ICID (2008)

566 **Fig. 1 – Scheme for determining total irrigation costs**

Fig. 2 – Results: Water price index by region

Fig. 3 – Results: Global irrigation water use

Fig. 4 – Results: Global irrigated land

Fig. 5 – Results: Global agricultural water use intensity

Fig. 6 – Results: Irrigation methods (global)

III.3. SBA BIODIVERSITY Publications by GEO-BENE Consortium Partners

ECOLOGY

Toward a Global Biodiversity Observing System

Tracking biodiversity change is increasingly important in sustaining ecosystems and ultimately human well-being.

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Biodiversity is a composite term used to embrace the variety of types, forms, spatial arrangements, processes, and interactions of biological systems at all scales and levels of organization, from genes to species and ecosystems (*1*), along with the evolutionary history that led to their existence (*2*). In part because of this complexity, universally applicable measures of biodiversity have proven elusive. Commonly used measures, such as the number of species present, are strongly scale-dependent and only reveal a change after species have been lost. Indices incorporating several proxy signals are potentially sensitive, but their arbitrariness obscures underlying trends and mechanisms. Integrated measures (*3*, *4*) are both sensitive and achievable, but more research is needed to construct the globally robust relations between population data, genetic variation, and ecosystem condition that they require.

The need for national to global-scale biodiversity measurements has been highlighted by the adoption of a target to "reduce the rate of loss of biodiversity by 2010" by the 190 countries that are parties to the Convention on Biological Diversity (CBD) (*5*, *6*). As we approach the target date, it is clear that this intention may suffer if we cannot effectively assess progress. The recent Conference of Parties to the CBD in Bonn, Germany, reinforced commitment to the goal, while acknowledging that much still needs to be done to reach it. Despite the absence of comprehensive data, there is little dispute that biodiversity continues to decline with uncertain, but potentially serious, consequences for society (*7*).

Unlike, for instance, the Framework Convention on Climate Change, there is no widely accepted and globally available set of measures to assess biodiversity. Consequently, the community has fallen back on a range of existing data sets gathered for other purposes. Currently, in the CBD process alone, there are ~40 measures reflecting 22 headline indicators in seven focal areas (see Biodiversity Indicator Partnership, www. twentyten.net). It seems unlikely that this set will provide clear messages to decision-makers (*8*).

There is no general shortage of biodiversity data, although it is uneven in its spatial, temporal, and topical coverage. The problem lies in the diversity of the data and the fact that it is physically dispersed and unorganized (*9*). The solution is to organize the information, to unblock the delivery pipeline between suppliers and users, and to create systems whereby data of different kinds, from many sources, can be combined. This will improve our understanding of biodiversity and will allow the development of fit-for-purpose measures of its condition over time. The proposed Group on Earth Observations Biodiversity Observation Network (GEO BON) is a new global partnership to help collect, manage, analyze, and report data relating to the status of the world's biodiversity.

The Group on Earth Observations (GEO) was launched in 2002 in response to the widely identified need for adequate information to support environmental decision-making. GEO is a voluntary partnership of 73 national governments and 46 participating organizations. It provides a framework within which these partners can coordinate their strategies and investments for Earth observation. The GEO members are establishing a Global Earth Observation System of Systems (GEOSS, www.earthobservations.org) that provides access to data, services, analytical tools, and modeling capabilities through a Web-based GEO Portal (www.geoportal.org). GEOSS has identified nine priority "societal benefit areas" in its first decade. Biodiversity is one of them. U.S. National Aeronautics and Space Administration (NASA) and DIVERSITAS, the international programme of biodiversity science, accepted the task of leading the planning phase of GEO BON, in collaboration with the GEO Secretariat.

No single organization could build a "system of systems" such as the one envisaged. Many local, national, and international activities exist to record various genes, species, and ecosystems, as well as the services they provide to society. GEO BON aims to create a global network from these efforts by linking and supporting them within a scientifically robust framework. For example, GEO BON will facilitate the combination of top-down measures of ecosystem integrity from satellite observations with a host of bottom-up measures of ecosystem processes, population trends of key organisms, and the genetic basis of biodiversity arising from the latest field-based and molecular survey methods. The role of GEO BON is to guide data collection, standardization, and information exchange. The participating organizations retain their mandates and data ownership, but agree to collaborate in making part of their information accessible to others.

The process to develop a GEO BON took shape in April 2008, when some 100 biodiver-

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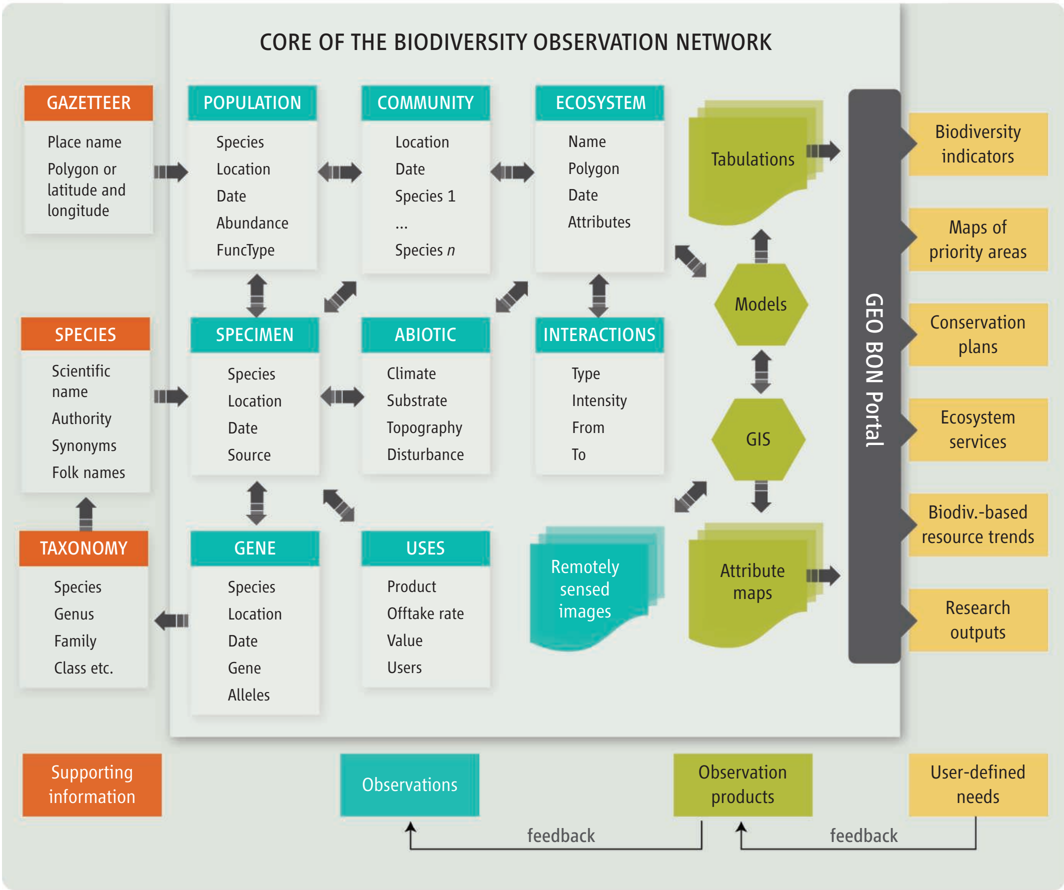

Integrated biodiversity observation system. The core data types, observation products, and end uses of an integrated biodiversity observation system are shown. Most of the elements already exist, but are incomplete or dispersed among a wide range of partners. The proposed implementation strategy involves linking them by using data-sharing protocols, followed by incremental, needs-led, and opportunistic growth. GIS, geographic information systems.

sity specialists representing over 60 scientific and intergovernmental organizations met at Potsdam, Germany, to complete the concept document. Seven working groups have been formed to draft an initial Implementation Plan by the end of the year. The key concept is a shared and interoperable system bringing data of different types and from many sources to bear on the information needs as defined by users (see figure, above). The primary data would include historical and future records from specimen collections in museums and herbaria, but also field observations by researchers, conservation and natural resource management agencies, and lay experts. A hierarchical sampling approach, involving millions of point observations of relatively simple data (e.g., the presence or absence of a species), thousands of records of abundance or community composition, and hundreds of detailed studies on individual ecosystems, bound together with models, remote sensing, and spatial analysis, would enable both global coverage and local relevance while remaining feasible and affordable. The supporting information and data-description protocols that allow this information to be shared among many independent sources are already relatively well-developed, thanks to the efforts, among others, of the Global Biodiversity Information Facility. They need to be expanded beyond collection records to include ecological observations. A biodiversity gateway on the GEO Portal, providing users easy access to data and the tools they need to understand it, will be an important part of the operational system.

The GEO BON initiative was noted by the Conference of Parties of the CBD at its May 2008 meeting, which requested the secretariat to "continue collaborating with the Biodiversity Observation Network with a view to promoting coherent biodiversity observation with regard to data architecture, scales and standards, observatory network planning, and strategic planning for its implementation" (*10*). Actions driven by the desire to adapt to and mitigate climate change, such as expansion of biofuel plantings and payments for avoided deforestation, emphasize the importance of reliable biodiversity information for other international conventions as well.

There are challenges ahead, including overcoming a tradition of data restriction within the biodiversity field. The initiative will require new kinds of cooperation among governments and nongovernmental organizations and between data providers and users of the information. The yardstick of success is not a cheaper global biodiversity observation system, but a more useful one and, thus, an improved cost-benefit relation. By analogy to the Global Climate Observing System (*11*), which is in more advanced implementation, it is estimated that the final total cost of a GEO BON could amount to €200 million to €500 million (U.S. $309 million to U.S. $772 million) per year. Because much of this is already committed in national agencies, the additional cost of global networking and gap-filling will be much more modest. The costs would be spread across many nations and organizations and phased in over a number of years, leveraging the existing expenditure in partial and stand-alone systems. The potential benefits are worth the extra effort.

References

1. R. F. Noss, *Conserv. Biol.* **4**, 355 (1990).
2. D. P. Faith, *Conserv. Biol.* **16**, 248 (2002).
3. R. J. Scholes, R. Biggs, *Nature* **434**, 45 (2005).
4. D. F. Hui, R. Biggs, R. J. Scholes, R. B. Jackson, *Biol. Conserv.* **141**, 1091 (April 2008).
5. A. Balmford *et al.*, *Science* **307**, 212 (2005).
6. H. M. Pereira, H. D. Cooper, *Trends Ecol. Evol.* **21**, 123 (2006).
7. "EU environment-related indicators 2008," www.energy.eu/publications/KH8107174END_002.pdf.
8. G. M. Mace, J. E. M. Baillie, *Conserv. Biol.* **21**, 1406 (2007).
9. The Royal Society, "Measuring biodiversity for conservation" (Policy doc. 11/03, The Royal Society, London, 2003).
10. CBD, *Monitoring, Assessment and Indicators: Follow up to the Millennium Ecosystem Assessment: Draft decisions for the 9th Conference of the Parties*, Bonn, Germany, 19 to 30 May 2008 (UNEP/CBD/COP/9/L.19, CBD, Montreal, Canada, 2008)
11. "Implementation plan for the Global Observing System for Climate in support of the UNFCCC" (GCOS-92) (Tech. doc. 1219, World Meteorological Organization, Geneva, October 2004).

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Right-sizing observation systems: a biodiversity example example using a cost-benefit approach

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Abstract

Although Earth observation systems are currently inadequate, hardly anyone can say what the optimum investment might be. An approach might be to size the system such that the marginal cost of a small incremental increase in effort is just more than the increase in net social benefit that results from the additional precision; and the savings from a marginal decrease in effort are less than the associated loss of social benefit. The approach is illustrated with an example based on wildlife survey in South Africa, made possible by a flourishing market for wildlife in the region, so the value per animal is reliably known, and the statistical benefit and incremental cost of increased observational effort are well understood. Results show that substantial increases in current survey efforts of high value animals are still possible before costs outweigh benefits. The study explores what this means for park managers and observation investment.

Keywords: Cost-benefit, wildlife census, value of information.

1. INTRODUCTION

It is widely accepted that the observation systems in virtually all spheres of environmental management are inadequate. What is less clear is the level of investment in observations that would be justified by the value of the resource and the risks of not knowing its true state. In other words, what is the 'stopping rule' for further investment in observing systems? Fritz et al (2008) proposed a conceptual framework for conducting such an analysis. It involves quantifying the costs of the observation system (conceptually not a difficult thing to do, but surprisingly seldom reported), and balancing this against the social benefits that are anticipated to accrue from the system. The procedure for quantifying the economic benefits of improved environmental information is poorly developed, largely because the logic for assigning value to ecosystems and their services is quite recent. The conceptual framework argues that in the absence of quantified economic data, the analysis should at least be explicit about the pathway ('benefit chain') through which the observations are anticipated to deliver their value. A further analysis would assign qualitative functions to the key steps in the benefit chain, to help decision-makers understand whether the break-even point for the observation system is likely to be far away or close by.

The purpose of this paper is to provide a simple worked example of the logic outlined in Fritz et al (2008). It takes advantage of the abundance of information in a particular field of earth observation – wildlife census (Norton-Griffiths 1975). Not only are the costs well understood, but in the particular context of South Africa, benefits can be reliably quantified as well. This is because a large and well-functioning market exists in South Africa for wildlife. Furthermore, many wildlife-based enterprises count their game stocks as part of their asset register. Therefore, knowing what the stock is has a quantifiable economic benefit.

2. MARGINAL BENEFITS AND MARGINAL COSTS

Wildlife conservation areas in Africa and elsewhere are typically periodically censused by flying a light aircraft carrying several observers at low speed and low altitude over the terrain, counting the animals observed within defined strips on either side. Generally such a census is a partial sample rather than a complete count, in that when the aircraft returns for the next transect, the strips are not contiguous, but have a gap between them. The cost of such a census typically has a fixed component (e.g. investment in the aircraft) and a variable component (the fuel and maintenance costs, the time of the pilot, biologist-observers and data analysts) which scales with the number of transects flown. As the sampling effort increases (i.e., the number of transects flown increases), the uncertainty of the estimate decreases asymptotically. When asked 'how much sampling is enough?' the wildlife biometrician will typically answer something like 'the effort which reduces the coefficient of variance for the target populations to within 10%' or some similar arbitrary number.

The example developed in this paper is based on data from the Kruger National Park (KNP), South Africa (Kruger et al. 2008). This national park covers 18989 km^2 and the large herbivores have been counted annually in the way described above from 1998 to the present time. (Aerial census in KNP began in the 1960s, but the techniques were slightly different).

Table 1. Numbers, census variability and price per animal for major herbivores in the KNP. The densities are the average 1998-2007, and the Coefficient of Variation (CV) is the median for the years. The Value per animal is for 2007, from the database maintained by the Unit for Wildlife Economics, University of the Free State (www.gamefarmnet.co.za/veiling.htm) and the KwaZulu-Natal Parks Board. Exchange rates June 2008 (1 USD = 7.62 ZAR)

Species	**Elephant bulls**	**White Rhino**	**Impala**	**Giraffe**	**Zebra**
Density (#/km2)	0.11	0.28	4.64	0.31	1.14
CV (%)	15.4	15.1	11.3	13.6	13.1
Value (USD)	39 370	38 921	95	1 938	643

Species	**Wildebeest**	**Kudu**	**Warthog**	**Water-buck**
Density (#/km2)	0.54	0.31	0.12	0.15
CV (%)	23.1	15	40.6	31.8
Value (USD)	203	303	106	670

The IIASA-coordinated EC project GEO-BENE provided financial support.

The counts were conducted using a Partenavia Observer twin-engined aircraft, at a height of ~76 m above ground level and a speed of ~ 170 km/hr. The strip width on either side was up to 400 m, but a distance-weighting function was used that means the 'effective width' on either side was about 200 m. The sampling intensity corresponding to the CVs given in table 1 was 15% of the surface area of KNP. The cost for this sample intensity is estimated at USD 70 000.

The ideas presented in the following section are based on a logic elaborated by Possingham in Mace et al. (2008). The upper limit of the economically-rational sampling effort is given by the point at which the cost of an additional unit of effort is more than the value delivered by that effort. In the case of a wildlife area where the financial performance of the entity is judged by the increase in its asset balance sheet, and where that balance sheet includes the value of wildlife (neither of which apply to the KNP, but rather to many other protected areas in South Africa), the value can be equated with the number of animals that can be confidently claimed to exist in the area, multiplied by their market value per head. For this example, we have selected the lower 99% confidence limit as the marker. The 'marginal value' of an increment of sampling effort is the increase in value that results from it because a more intense sample has a lower error range, and therefore the number of animals that can be claimed increases. By this logic, the sample effort in the KNP case could be increased 95 times before the increase in costs exceeds the increased value (Table 2).

Table 2. Sample effort (n) at point of breakeven (where cost:benefit = 1) for each species and for all combined

Species	n
Elephant bulls	38
W Rhino	71
Impala	8
Giraffe	10
Zebra	11
Wildebeest	5
Kudu	4
Warthog	3
Waterbuck	6
All	95

This is largely because many of the species being censused have a very high value (Table 1). Note that the total value of the wildlife in KNP is substantially underestimated in this example because, for instance: only mature elephant bulls are counted (the calves and females from large herds are not well censused by this technique); aerial counting underestimates the true number of most species (other methods show there are at least twice as many white rhino than indicated in Table 1); and a long list of rare or hard-to-see species are not reported.

As a test of the logical validity of the approach, consider the case of a low-value species, such as warthog, where the census variance is high; here breakeven occurs at double the current sampling effort. For similar low value species with lower variance breakeven takes place at sample efforts 3 to 8 times current effort.

3. THE VALUE OF INFORMATION

In the case of the Kruger National Park, it can be rightly argued that this theoretical upper limit for sampling effort is inappropriately high, since the total value of animals in the park is not a valid reflection of their social value. If the numbers fluctuate up or down a bit, no social value is really created or destroyed. So why do the KNP manages need to know how many animals there are, how accurately do they need to know the number, and what is the economic value associated with improvements in this information?

The KNP has a highly-explicit management plan based on adaptive management. It permits wildlife populations to fluctuate within bounds known as 'thresholds of potential concern (TPC)'. In the expert opinion of the park ecologists, knowledge of large herbivore populations with a less than 15% coefficient of variation, on an annual basis, is sufficient to detect trends in the populations that might transgress a TPC in time to intervene. Using our data and approach we can calculate that in the instance of the highly topical elephant population, currently growing at a near-maximum rate and believed to have an upper TPC defined by the impact that elephants have on tree populations, a <15% CV would require only a very modest (10%) increase in sampling effort. On the other hand, a <15% CV for wildebeest, a species whose numbers have fallen sharply since the 1960's construction of park boundary fences, which restrict their migration, would require a trebling of sampling effort.

Is a 15% CV adequate for this purpose? Given that the elephant populations are growing at close to 6% per annum (van Aarde et al. 2008), the CV would need to be about 3% to have a 95% probability of predicting the transgression of a threshold in the following year, based on year-to-year trend projection. This would translate into an approximately 25-fold increase in effort. In practice, elephant populations have high inertia due to the longevity of the animals, so multi-year trend detection can be used, reducing the sampling effort needed to detect a TPC transgression in good time.

Intervention in wildlife population dynamics is a very expensive business, at a variety of levels. For instance, deciding to cull elephants when it was not in fact necessary to do so, could potentially have a multi-million dollar impact on the tourism industry, which is increasingly sensitive to animal rights concerns. One of the alternatives is the use of contraception. Halting the elephant population growth trend would require: 1) action to begin about a decade before the threshold is reached; and 2) imposing infertility in about 75% of the females in the population. The costs of repeated immunocontraception of free-ranging elephants are estimated at approximately USD 130 per female per immunisation, of which three are required, about a year apart (Bertschinger et al. 2008). For the KNP population of about 5000 reproductive females, this translates to about USD 650 000 pa in the first three years, and ZAR 65 000 pa every year thereafter. Beginning an operation of this scale too early has significant financial consequences. On the other hand, beginning too late threatens the integrity of an ecosystem on which many other species, and a multi-billion ZAR tourism industry, depend.

4. CONCLUSIONS

1. The economically-rational investment in environmental observing systems should scale with the value or social benefits of the assets being observed and the risk of loss or damage that they face.
2. In many cases, the value of the environmental asset will be quantifiable using the logic of ecosystem services, i.e. the benefits that society obtains from nature.
3. In the case of wildlife census in South Africa, there is a strong case that the current effort expended in quantifying the populations of high –value species is well below the optimum levels.

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REFERENCES

Bertshinger, H. and A. Delsink. 2008. Reproductive control of elephants. In: RJ Scholes and KG Mennell (eds) Elephant Management: a scientific assessment for South Africa. Wits University Press, Johannesburg. pp 257-328.

Kruger, J.M., B.K. Reilly and I.J. Whyte. 2008. Application of distance sampling to estimate population densities of large herbivores in Kruger National Park. Wildlife Research 35, 371-376

Fritz, S., R.J. Scholes, M.Obersteiner , J. Bouma and B. Reyers. 2008. A conceptual framework for assessment of the benefits of a Global Earth Observation System of Systems. *IEEE* 2 (3): 338-348

Mace, G.M, H.P. Possingham and N. Leader-Williams. 2008. Prioritizing choices in Conservation. In: D Macdonald and K Service (eds) Key Topics in Conservation Biology. Cambridge University Press, UK. pp 17-34.

Norton-Griffiths, M. 1975. Counting animals. African Wildlife Leadership Foundation, Nairobi.

Van Aarde, R,S. Ferriera, T. Jackson and B. Page. 2008. Elephant population biology and ecology. In: RJ Scholes and KG Mennell (eds) Elephant Management: a scientific assessment for South Africa. Wits University Press, Johannesburg. pp 84-145.

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Potential impacts on important bird habitats in Eiderstedt (Schleswig-Holstein) caused by agricultural land use changes

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ABSTRACT

Agricultural land on the Eiderstedt peninsula in Schleswig-Holstein (Germany) is traditionally dominated by extensively used grassland. These grassland areas are home to many (endangered) bird species, making Eiderstedt one of the prime bird habitats at the west coast of Schleswig-Holstein. Plans exist to convert large shares of grassland to arable farmland to grow crops needed in an intensified dairy production and for biofuels. In this study, three possible scenarios of agricultural land use change on Eiderstedt in the next couple of decades are developed. Using a Geographic Information System (*GIS*), the possible impacts of such conversions on breeding bird populations of four key species are determined. The results indicate that an increase of arable farmland to approximately two thirds of the whole agricultural area drastically reduces suitable bird habitat, thus considerably diminishing the number of breeding pairs supported by the environment. The ornithological impact is greatest if conversion takes place throughout Eiderstedt extending from already existing areas of arable farmland. But even though the reduction in suitable breeding habitat is less pronounced in the other scenarios, every one of them induces a severe pressure on populations of meadowbirds that rely on habitat on Eiderstedt for successful reproduction.

Introduction

The Eiderstedt peninsula at the west coast of Schleswig-Holstein (Germany) is a mainly agriculturally used land area, which is also home to many bird species breeding along the shores adjacent to the Wadden Sea. Also, vast amounts of birds migrate through this region on their way from their wintering grounds in the south to the Arctic and back. Hötker, Köster, and Thomsen (2005) consider Eiderstedt to be one of the most important habitats for meadowbirds in whole Germany.

Currently, most of the agriculturally used land on Eiderstedt is extensively used grassland. In recent years, however, a growing share of the agricultural land is used as arable farmland to grow corn, etc. because of an increase in demand for energy-rich food for cattle and fuel for biogas plants that are to be built in the area (Husumer Nachrichten, 2006). In addition, the extensively used grassland is more and more converted into intensively fertilized meadows for dairy production. Such large-scale transformations of agricultural land are likely to have a considerable influence on those bird species that depend on grassland as breeding habitat (Bauer, 1997).

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In this study, we determine the relationship between the occurrence of birds breeding on Eiderstedt and the characteristics of their breeding habitat. Using this information in a Geographic Information System (*GIS*), we assess the possible impacts of a continued agricultural land use change in the next two decades on the suitability of Eiderstedt as a principal breeding habitat for birds in Northern Germany and therefore on the expected abundance of breeding birds in this region.

Agricultural land use changes on Eiderstedt

The Eiderstedt peninsula is located at the west coast of Schleswig-Holstein (Germany). It lies between the river Eider and the city of Husum and extends into the North Sea (Fig. 1). Until the 11th century, Eiderstedt consisted of several smaller geest islands which became connected after the area was enclosed by dikes (Meier, 2001). Today, the Eiderstedt coastline is entirely protected by dikes.

The soil quality of the marshland is high (Feddersen, 1853; InfoNet Umwelt, 2007). But in order to utilize the land agriculturally, it is necessary to maintain a functioning drainage system. Besides a dense network of narrow trenches between the fields, parallel passing drills (in German: *Grüppen*) that additionally drain the grassland areas are typical for Eiderstedt (Fischer, 1997).

Up to the 18th century, cultivation of crops was one of the prime means of agricultural use of the land, but even though a large share of land was used as arable farmland, the predominant type of agricultural land was grassland. Around 1850, cattle farming increased in importance, as exports to the United Kingdom via the harbors of Tönning and Husum grew quickly (Hammerich, 1984). This called for a considerable extension of opportunities for grazing. In the following decades, the share of grassland sometimes even exceeded 90% (LVermA-SH, 2007a). After World War II, the share of grassland on Eiderstedt decreased from close to 90% to approximately 75% in the 1970s (Table 1) and remained stable at this level until recently (Stat A Nord, 1950–2004).

In recent years, the characteristics of cattle farming on Eiderstedt shifted towards a more intensive approach. Cattle for meat production generally remains in cow barns, while the cattle used in dairy production is held on grassland, which is often heavily fertilized. The increased number of cattle held necessitates the growth of large amounts of forage crops in adjacent areas, mainly corn. Since the total agricultural land area on Eiderstedt is limited, this led to a considerable increase in the share of arable farmland on Eiderstedt since 2003 and a concurrent reduction of grassland. Adventitiously, enhanced grassland conversion takes place because of fuel production for biogas plants.

The local farmers union plans to extend the amount of land used to grow forage crops to approximately two thirds of the agricultural land area in the next couple of decades (NABU, 2004). This plan is intensely debated and opposed by local environmental organizations who claim that such a large-scale shift in land use not only alters the overall appearance of the whole region but also has devastating effects on the breeding bird colonies, as arable farmland on which corn is grown is much less suitable as habitat than extensively used grassland (Beintema, 1983). Therefore, realization of the farmers' plans would greatly impact the local carrying capacity of many (endangered) bird species.

Eiderstedt as important habitat for breeding and migrating bird species

Grassland is often an important substitute for lost natural habitats such as moors, salt marshes, or other wetlands. Eiderstedt offers ideal breeding conditions for meadowbirds owing to its large share of grassland and meadows with many ponds and drainage trenches that are extensively used by the local agriculture.

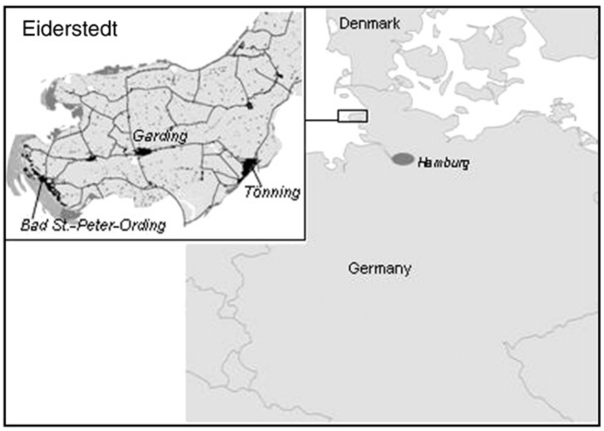

Fig. 1. The Eiderstedt peninsula.

Table 1
Agricultural land use on Eiderstedt from World War II until present (Stat A Nord, 1950–2004)

Year	Total agricultural land area (ha)	Share of grassland (%)	Share of arable farmland (%)
1949	23691	80	20
1960	23264	84	16
1970	25771	90	10
1979	25973	80	20
1983	25943	75	25
1987	25504	74	26
1991	25698	76	24
1995	25504	78	22
1999	24668	77	23
2003	24016	73	27

The Eiderstedt peninsula is an important breeding area of the Northern Lapwing (*Vanellus vanellus*), the Eurasian Oystercatcher (*Haematopus ostralegus*), the Black-tailed Godwit (*Limosa limosa*), and the Common Redshank (*Tringa totanus*) in Germany (Hötker et al., 2005). Despite considerable measures to protect the populations of these species, their abundance has decreased dramatically during the last few years. Northern Lapwing and Common Redshank are considered to be endangered; the Black-tailed Godwit is even listed in the category of being severely threatened by extinction (Bauer et al., 2002; Knief et al., 1995). On the other hand, the abundance of the Eurasian Oystercatcher has increased recently.

The selected bird species depend on low and sketchy vegetation on wet meadows or marshes (Gillmor et al., 1998). Some prefer the proximity to open waters but all avoid fallow lands and cut meadows (Hoffmann, 2006). These species can also serve as indicators in land use intensity assessments (Beintema, 1983). While Eurasian Oystercatchers and Northern Lapwing are also found on intensively used grassland and sometimes even breed on arable farmland, Common Redshank and particularly Black-tailed Godwit have higher demands regarding the quality of the grassland (Beintema, 1983; Hoffmann, 2006).

Methodology

Aims and methods

Conversion or the abandonment of extensively used grassland to either arable land, intensively used grassland or fallow land with forest succession can be observed throughout Europe. Such land use changes are often motivated by political decisions and demographic or socio-economic trends (Bauer et al., 2002). Regardless of the reason, a loss of valuable habitat can generally be registered as a consequence of such land conversion (EEA, 2004). This has implications for the ornithological fauna, which manifest themselves in the fact that many farmland bird species have been declared endangered species in Europe over the last few decades and that their decline has become an important conservation concern (Bayliss, Simonite, & Thompson, 2005).

This study aims to improve the understanding of the potential impacts of land use changes on key species of the local bird fauna by exploring a set of possible land use development scenarios. We focus on four bird species with mapped field distribution as key species. The following questions serve as guideline for the assessment:

1. Which processes cause the land use change and how can these be transformed into future land use scenarios?
2. How are the breeding habitats of the key species characterized and how can these be assessed concerning its site and habitat suitability?
3. To what extent do the habitats change qualitatively and quantitatively in the land use change scenarios?
4. What implications does it have on the key species?
5. Can general statements about grassland conversion be deducted from the findings?

Several empirical models already exist, which can be used to analyze the distribution and habitat suitability of species. Most of them model the potential distribution of certain single or multiple species (Bayliss et al., 2005; Cabeza et al., 2004; Manel, Dias, & Ormerod, 1999; Seoane, Bustamante, & Díaz-Delgado, 2004). Bayliss et al. (2005) use a multi-species approach that utilizes Bayesian decision rules, others like Seoane et al. (2004) apply predictive habitat models or general linear models (*GLMs*) (Granadeiro, Andrade, & Palmeirim, 2004; Guisan, Edwards, & Hastie, 2002). In our assessment, the emphasis lies on the utilization of existing field data of bird occurrence and their extrapolation in accordance with different land use change scenarios. The analysis is conducted with a *GIS*-based model that is explained in more detail below.

GIS methods have already been used in some studies to determine species distributions. For example, Thompson, Hazel, Bailey, Bayliss, and Lee (2004) identify locations of potential breeding sites of curlews and Powell, Accad, and Shapcott (2005) analyze species distributions using biotic and abiotic factors to predict former ranges of species. They also demonstrate that simple rule-based non-statistical models can be effective tools for such applications. However, the integration of scenarios into *GIS*-based modeling of species habitats has been often neglected so far. This necessary step forward, which allows the application of the results in effective land use planning and conservation management, is taken in this study.

Data and software used in the assessment

In order to be able to determine the potential impacts of future land use changes on the breeding populations of the bird species in question, it is necessary to look at the historic land use development as it defines the current situation on Eiderstedt. This is done using survey data on agricultural production in Schleswig-Holstein provided by the Statistics Department Nord, which allows us to assess the period from the end of World War II until present (Stat A Nord, 1950–2004). Together with *GIS* data on current land use on Eiderstedt, provided by the Landesamt für Natur und Umwelt des Landes Schleswig-Holstein (LVermA-SH, 2007b), and data on the abundance of key bird species breeding in the area (Hötker et al., 2005), it is possible to relate the preferred breeding habitats to agricultural land use decisions. *ArcGIS* 9.1 and 9.2 as well as the analysis tools V-late (Tiede, 2005) and Hawths Analysis Tools (2006) are used in this assessment.

The development of agricultural land use in recent decades is extended into the future for another 20 years. The projections are based on political intentions to drastically increase the share of arable farmland up to two thirds of all agricultural land on Eiderstedt (NABU, 2004) and assumptions about the possible patterns of land use change. As these changes alter the suitability of the land to serve as breeding habitat for meadowbirds, they can be expected to have a profound influence on the number of breeding pairs on the peninsula. The extent of the ornithological impact is quantified using a measure of dynamic habitat sensitivity of the potential breeding areas.

The Habitat-Sensitivity-Index as measure of biotope quality changes

We developed an assessment scheme to determine how landscape changes affect the characteristics of breeding habitats of birds. This scheme includes the transformation of ecological facts, effects and connections into indices that can be used in an objective interpretation (see Bastian & Schreiber, 1999; Weis, 2007). The habitat assessment relies on a combination of specific algorithms that allow integrative and complex statements (Bastian, 1997). Together with the results of the scenario analysis, these statements are projected into future conditions and compared with each other. This allows assessments of the impact potential of land use change and the sensitivity of the landscape. The following equation provides the basis of the habitat assessment. The habitat sensitivity (*HaSI*) of each patch of land i is a combined measure of three key indices: the proximity index (*PX*), the neighborhood quality index (*NI*), and the patch size index (*SCI*). *DI* denotes the habitat demand index:

$$HaSI_i = \frac{\sum_i (PX_i, NI_i, SCI_i)}{3} \forall DI \in [4, 5]. \tag{1}$$

A fundamental element influencing habitat sensitivity is the development of the suitability of land as ornithological habitat. It is described by a habitat demand index (*DI*). This index measures the suitability of a number of land cover parameters for selected breeding birds. Sites that have a relatively unfavorable natural character but serve as habitat for the majority of breeding birds can receive a fairly high index value as well. The supply (of nature) is related to the demand of the potential user (in this case endangered bird species).

The analysis of the habitat demand of selected bird species is based on the procedure of a habitat suitability analysis conducted by Lang and Blaschke (2007). The data used here are adapted from occurrence maps of selected breeding birds of 2001. Spatial land use and biotope data are from 1991 to 2002. In our analysis, we determine the preferred habitats of the selected bird species. In a first step, the occurrence data are intersected with the biotope and land use maps to identify the preferred habitat types. The results, which are expressed as proportional shares, are subsequently transformed into ordinal classes with five categories, the *DI*. Because we use data on breeding birds only, it is necessary to supplement the data with further information from literature (Gillmor et al., 1998; Gruber, 2006; Hoffmann, 2006; Morrison, Marcot, & Mannan, 1992) to avoid uncertainty errors as described in Lang and Blaschke (2007). The *DI* categorizes the degree of general habitat suitability, which is the basis for further analyses. The resulting list of suitable and therefore valuable habitats for the selected bird species is space independent and yields information on a functional level. Biotope types with a *DI* of 4 and 5 (suitability level of 60–100%) are considered to be potentially extraordinary or very suitable habitats, whereas a *DI* of 3 (suitability level 40–60%) refers to conditionally suitable or partially suitable habitats. *DI*s of 2 and 1 (suitability level 0–40%) are unsuitable as habitats for the selected bird species and are omitted in the following model analysis.

The results gained above are spatially transformed to fit the biotope data of Eiderstedt and the areas with high habitat suitability, i.e. a *DI* of 4 or 5, are selected for further analysis. These particularly suitable habitats are the basis for the isolation assessment via the *PX* (Gustafson & Parker, 1992). The proximity evaluation is conducted with the tool V-late (Lang & Tiede, 2003) for *ArcGIS* and allows the rating of individual patches of land according to its functional network with the surrounding habitats (Kiel & Albrecht, 2004). The *PX* distinguishes between space dispersal and clustered distribution of habitats by considering the size as well as the distance of the patches, as both quantities are important for the assessment of habitat complexes. We use 2002 as base year with a buffer of 250 m for the *PX* evaluation. The results are transformed logarithmically and split into five classes (based on Weis, 2007). For comparability, the same divisions are applied in the subsequent scenario analyses. The index increases with area size and decreases with distance to similar patches of land. The index value is highest if a patch is surrounded by and/or extending towards nearby biotopes of the same kind (Lang & Blaschke, 2007). Table 2 shows the classification scheme of the *PX*.

Another important aspect in the evaluation of habitat sensitivity is the character of the environment (Bastian, 1997), since it also plays a role in the habitat choice of the bird species (Newton, 2003). In our assessment, this is denoted by the neighborhood index (*NI*). It is assumed that the *NI*, and therefore the attractiveness of the area for the selected bird species, declines with a diminishing quality of the surrounding environment. We follow the assessment of Weis (2007). The *NI* can only be calculated if the following information on habitat quality is given.

The quality of the neighborhood is determined by the *BQ* index (cf. Schlüter, 1987). The *BQ* consists of an assessment of all characteristics of an area under utilization-specific aspects. This index value is represented by a combination of the hemeroby index (*HI*) and an index of the conservation value (*CI*).

$$BQ = \frac{HI + CI}{2}. \tag{2}$$

Hemeroby is based on vegetation and depends directly on human utilization intensity and pressure. It assesses how pristine a considered biotope is, given the influence of anthropogenic cultivation present. Schlüter (1987) developed a scale to rate biotopes based on their vegetation. For our purposes, this scale is adjusted to yield five index classes by aggregating two levels into one index class. Generally, open waters do not fit into this scheme. However, the North Sea and the river Eider are included in our assessment and rated as $HI = 5$ because these waters are of significance for the adjacent salt marshes and the bird species considered in this study. The index values for the open water are also important to prevent a bias in the classification of the *NI*. The *HI* is closely connected to the biological regulation and regeneration capacity. The lower the *HI*, the more limited the regulation and regeneration potential of the biotope is. This allows inferences about the ecological stability of assessed landscapes.

In addition to the *HI*, the *CI* is a second measure of biotope quality. Each biotope is evaluated according to its general importance for species and biotope conservation. We apply the assessment scheme presented in Bastian and Schreiber (1999) which is adapted to fit our model. The base data are provided by a biotope map of 1991 (LANL, 1993) that is classified in a *GIS*. As before, index values between 1 and 5 are assigned to each biotope type based on its general conservation value. Table 2 lists the classification schemes of habitat quality for each biotope type. The characteristics of all index classes are described in Table 3.

To obtain the *NI*, a buffer of 250 m is applied to all areas. The area-relevant mean value of *BQ* is determined for each patch (Bastian, 1997). The difference between the *BQ* of the habitat and that of its surrounding is a measure of the quality of the neighborhood (Weis, 2007). It is expressed in five index classes.

The size of a patch is also of importance when considering its neighborhood. The larger the habitat, the less is it influenced by its surroundings. To integrate the habitat size, the area of each habitat is determined and categorized by five area size classes *SCI* (Table 2).

Table 2
Index classes of different biotope types on Eiderstedt used in the analyses

Index	*PX*	*BQ*	*NI*	*SCI* (ha)
1	0.000–1.231	Roads, other paved areas	0.0–2.0	0.0–2.0
2	1.232–2.569	Settlements, arable farm land	2.1–2.5	2.1–10.0
3	2.570–3.453	Intensively used grassland	2.6–3.2	10.1–40.0
4	3.454–4.211	Extensively used grassland, beaches, dunes, ponds	3.3–4.0	40.1–100.0
5	4.212–6.078	Marsh land, salt marshes, forests, open water	4.1–5.0	>100.0

Table 3
Description of index values

Index	*PX*	*NI*	*HaSI*
1	Isolation of small habitat patch is extremely high	Quality of the surrounding area is extremely unfavorable	Extremely low bird habitat quality. No ecological value for selected bird species
2	High isolation or very small habitat patch	Neighboring areas of worse ecological quality	Low habitat quality with minor value for selected breeding birds
3	Medium isolation or medium sized habitat patches	Medium neighboring quality	Medium habitat quality but still of value for selected bird species
4	Habitat patches build small complexes or are of bigger size	Good biotope quality of the neighborhood	Good habitat quality with significant value for selected breeding birds
5	Very high complexity or extending patch size	Excellent biotope quality of the surroundings	Excellent habitat quality with very high ecological value for selected breeding birds

Table 4
The average breeding pair density for each habitat sensitivity index (*HaSI*) class (breeding pairs/ha) and the total expected bird abundance in all scenarios

Bird species	*HaSI*	Density	2002	S1	S2	S3
All species	1	0.04	4	87	62	20
	2	0.47	1164	619	877	1042
	3	1.21	11235	3272	3358	4179
	4	1.87	17252	1343	720	1180
	5	2.84	3240	903	0	372
	Total		32895	6224	5017	6793
Eurasian Oystercatcher	1	0.03	3	64	47	15
	2	0.12	292	158	224	266
	3	0.31	2973	838	860	1195
	4	0.52	4804	373	200	328
	5	0.65	740	207	0	85
	Total		8812	1640	1331	1889
Common Redshank	1	0	0	0	0	0
	2	0.02	58	26	37	44
	3	0.06	564	162	167	231
	4	0.13	1160	93	50	82
	5	0.23	265	73	0	30
	Total		2047	354	254	387
Black-tailed Godwit	1	0	0	0	0	0
	2	0.03	86	40	56	67
	3	0.08	732	216	222	308
	4	0.19	1652	136	73	120
	5	0.37	420	118	0	48
	Total		2890	510	351	543
Northern Lapwing	1	0	0	0	0	0
	2	0.09	230	119	168	200
	3	0.24	2208	649	666	925
	4	0.34	3148	244	131	215
	5	0.67	765	213	0	88
	Total		6351	1225	965	1428

The *HaSI* integrates all elements described above and allows an assessment of the state of the landscape with special consideration of the necessities of the selected breeding bird species. The *HaSI* is first determined for the base year 2002, which is the reference for the comparison with the different scenarios of land use development on Eiderstedt.

Implications for bird populations

Occurrence maps of the selected bird species are intersected with the *HaSI* index values to determine the mean breeding pair density for each *HaSI* class (Table 4). Because the bird data only map occurrence within the dikes, the outer salt marshes are excluded from further analysis. It is assumed that these areas, which often have the highest abundance of breeding birds, remain stable in size and carrying capacity. Under the condition that bird abundance per unit area is time independent, we incorporated the results into the scenarios, allowing calculations of the potential reduction of breeding pairs of the selected species. This assessment is conducted for each single bird species separately but also for all four species densities taken together.

Scenarios

In our assessment, we assume that the plan to drastically increase the amount of arable farmland on Eiderstedt is realized within the next couple of decades. Since the propositions do not contain any information on which areas are to be converted, three different patterns of land use change are considered in this analysis. They are shown in Fig. 2 together with the current agricultural land use on Eiderstedt (Fig. 2a).

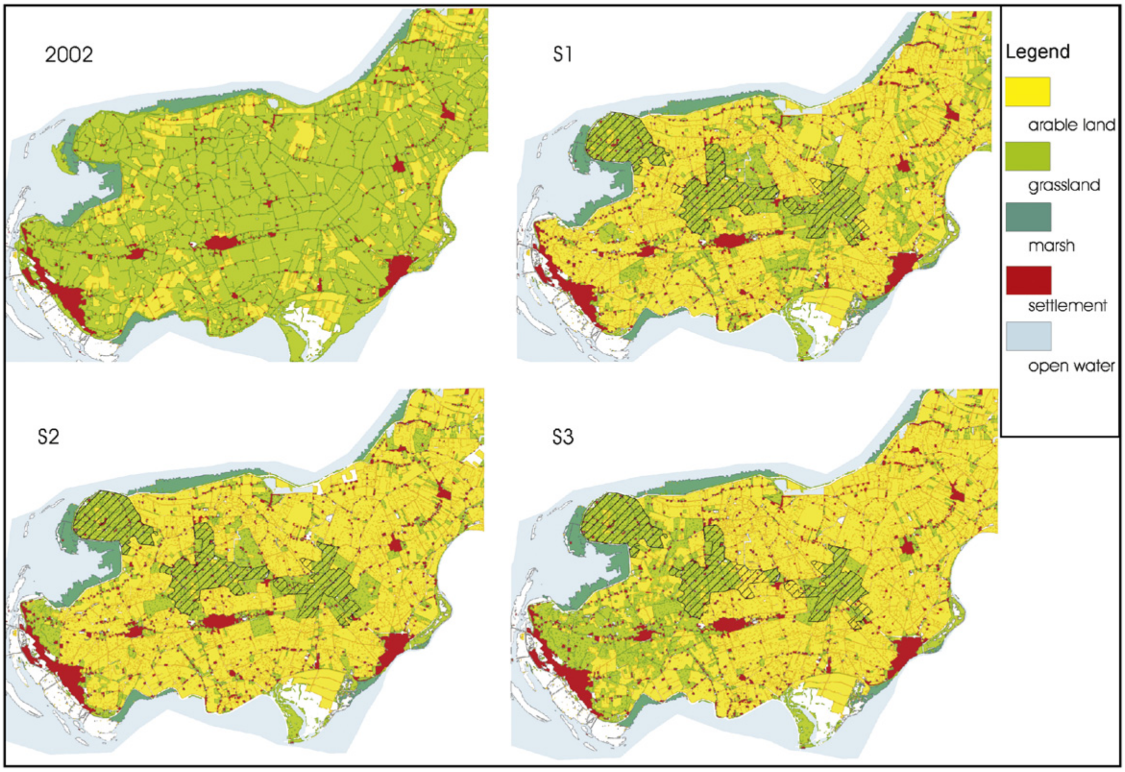

Fig. 2. (a) Land use on Eiderstedt in 2002; expected land use on Eiderstedt in the late 2020s if land use change occurs, (b) along main roads and newly diked areas (S1), (c) around already existing arable farmland (S2), (d) from east to west (S3).

In the first pattern of land use change, land is primarily converted along the main roads through Eiderstedt and preferably in only recently diked marshland (Fig. 2b), as the crops to be grown on the converted land need to be transported efficiently to the sites at which they are processed. Growing the crops as closely as possible to already existing infrastructure makes this task significantly easier. The second pattern is based on the assumption that it is best to grow crops on large continuous patches of land. Therefore, in this pattern land is primarily converted in areas around currently existing arable farmland (Fig. 2c). The third pattern of conversion follows the premise that the less remote an area of land is, the more useful it is to be used for crop production. Since the Eiderstedt peninsula is connected to the rest of Schleswig-Holstein only in the east, this pattern of land use change converts grassland to arable farmland from east to west (Fig. 2d). Further details about these scenarios are given in Link and Schleupner (2007).

Results

The agricultural land use patterns resulting from the planned conversion are identified for all scenarios. Afterwards, possible impacts on the populations attempting to breed on Eiderstedt are determined by considering the previously obtained information on the breeding habitat preferences of the bird species assessed.

Depending on the pattern of land use change, the scenarios lead to considerably different distributions of agricultural areas on Eiderstedt approximately two decades into the future. If the land use change originates from the main roads through Eiderstedt (scenario S1), patches of grassland remain throughout Eiderstedt (Fig. 2b). These are generally detached from one another, except for the areas around the three bird sanctuaries, in which larger uniform areas of grassland remain intact. These serve as primary breeding grounds for the remaining meadowbirds. It has to be noted that the political choice of declaring Westerhever a bird sanctuary is the only reason for not converting the northwestern tip of Eiderstedt into arable farmland.

The distribution of the remaining grassland in 2025 is similar in scenario S2, in which land use change radiates outward from already existing patches of arable farmland (Fig. 2c). The region north of St. Peter-Ording remains grassland and less land is converted in the vicinity of the two bird sanctuaries in central Eiderstedt. Patches converted to arable farmland are less fragmented, so that the degree of land use change appears to be even higher than in the previous scenario, even though this is not the case.

The resulting pattern is substantially different in scenario S3, which depicts a conversion of farmland progressing westwards (Fig. 2d). Practically all remaining grassland is located west of the town of Garding. Eastwards, only bird sanctuary of Kotzenbüll remains more or less intact, even though it has to be noted that there is even some land use change within the two sanctuaries in central Eiderstedt. This is likely to have an adverse influence on the overall habitat quality of these two special regions. Another caveat is that large parts of the remaining grassland are in the vicinity of the towns of St. Peter-Ording and Tating, which are popular tourist destinations at the west coast of Schleswig-Holstein. High frequentation of the areas surrounding the breeding habitats by humans can artificially reduce breeding success even though habitat conditions might be superior to those in the other two scenarios.

In the next step of the assessment, each patch of land is characterized based on the classification criteria outlined above. This way it can be determined how the altered land use patterns in all scenarios influence the suitability of the land as breeding habitat for the various bird species.

The *PX* yields information about the isolation or complexity of habitats. The analysis reveals that in 2002 areas with a high *PX*, i.e. a high complexity of habitats, are evenly distributed across the peninsula. Only very small patches and adjacent salt marshes have lower index values. The results of the neighborhood quality evaluation show the same pattern except that the salt marshes now have highest index values. In contrast to 2002, the index values are much lower in all three scenarios, but there are clear differences between the three cases considered. It is striking that the values for the salt marshes remain unchanged with the exception of the *NI* in S2, in which they suffer from extremely reduced biotope quality in neighboring biotopes.

After integrating all intermediate results into the *HaSI* equation, it is possible to draw conclusions about changes in habitat quality. *HaSI* ranges from 1 to 5, with class 1 referring to the lowest possible habitat quality with almost no ecological value for the selected breeding birds. The *HaSI* for 2002 and for the three scenarios is illustrated in Fig. 3. In 2002, there were 26,132 ha of valuable habitats for the selected birds. This amounts to 70% of the total land area of Eiderstedt. The habitats are evenly distributed throughout the peninsula. Seven patches of land are rated with the highest *HaSI* value of 5. These are the salt marshes along the northern coast, as well as patches situated in the northern half of Eiderstedt. Only one of these patches is located in the southwestern part close to St. Peter-Ording. The habitats in the northern and eastern parts of the peninsula obtained mainly high *HaSI* values of 4, whereas the lower values of 2 and sometimes of 1 are generally found in the south.

The three scenarios of possible development of agricultural land use are now compared to the reference state of 2002. Besides the reduction of total suitable habitat area, changes in *HaSI* of the remaining suitable breeding habitats are evident. Only in scenario S3 one of the former patches with an index value of 5 remains, all others are either converted into arable farmland or have a deteriorated *HaSI*. In S1, the most suitable habitats shift towards the center of Eiderstedt. In S2, areas with the highest *HaSI* no longer exist and also the second highest index class is only found in four areas. Table 5 shows the

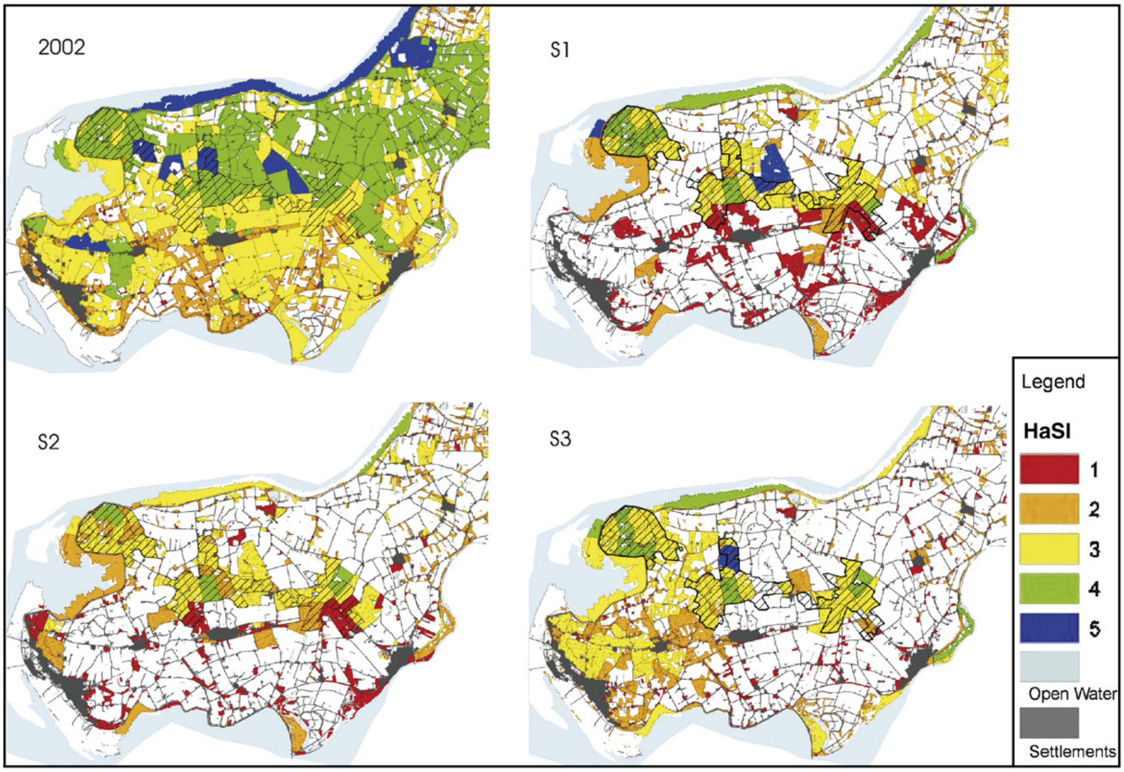

Fig. 3. The *HaSI* for (a) 2002, (b) scenario S1, (c) scenario S2, (d) scenario S3.

Table 5
Shares of land area (%) for each *HaSI* class in the three scenarios and the reference year

HaSI	2002	S1	S2	S3
1	0.4	30.1	23.6	6.9
2	11.1	18.2	28.4	30.2
3	41.8	37.4	42.2	52.5
4	41.5	9.9	5.9	8.6
5	5.1	4.4	0	1.8

share of the area for each *HaSI* class. It highlights the differences between all three scenarios but also gives the overall proportional changes in habitat quality. The area of habitats with lowest *HaSI* increases considerably in all scenarios. While in 2002 only 0.4% of the area is rated with *HaSI* of 1, the amount of land in this category increases to 7% in S3. In S1 it even reaches nearly one third of the demanded area. The most dramatic change occurs with land that is fairly well suited as breeding habitat ($HaSI = 4$): in 2002, 41.5% of the total area is of this habitat quality, whereas after the presumed land use change only 6–10% of the remaining area is still well suited as breeding habitat. To sum up, in all three scenarios large amounts of previously highly suitable habitats are degraded to sites with medium or low habitat value.

The results of the habitat sensitivity analysis are used to obtain average breeding pair densities of the selected bird species for each *HaSI* class. First of all, the breeding pair density is determined for each bird species and in total for the base year 2002. The breeding pair density of all four species considered is positively correlated with the *HaSI* (Table 4). This is a very convenient finding, as it also verifies the methodology of the *HaSI* evaluation. Only few Eurasian Oystercatchers breed on patches with a poor *HaSI*, while all other birds prefer higher quality habitats. Assuming that the bird densities remain stable for each *HaSI* category, it is possible to calculate the potential abundance of breeding birds in each scenario. Table 4 gives an overview of the breeding pair density per *HaSI* and the resulting bird abundances. The scenarios point to considerable impacts on breeding habitats caused by large scale agricultural land use changes: there is not only a loss of total habitat area of approximately two thirds, but also a shift in the quality of the habitats. The combination of these effects leads to an expected decrease in bird abundance of more than 60%. Compared to the 32,895 breeding pairs of all four bird species in total in 2002, the number of pairs should decrease to about 11,000 pairs. The actually determined expected number of breeding pairs shown in Table 3 is even lower since the reduction in suitable land area brings about a decline in quality of the remaining habitats. The number of breeding pairs declines by another 50% in some scenarios due to this additional effect.

Discussion and conclusion

One aim of this study is to pinpoint the potential impacts of land use changes to species habitats of agricultural landscapes. In contrast to other studies that often model species habitats based on past or present habitat conditions (e.g. Bayliss et al., 2005; Seoane et al., 2004; Thompson et al., 2004), this assessment considers potential future land use changes. This necessitates the use of special scenarios to spatially extrapolate the landscape changes, which methodologically extends already existing habitat suitability models.

Agricultural land on the Eiderstedt peninsula is traditionally dominated by extensively used grassland even though the share of grassland in relation to arable farmland was fairly variable in the past. The knowledge of past land use changes and its regional causes are important for the development of future scenarios. The scenario analysis applies three possible paths of land use development on Eiderstedt in the next couple of decades. In all of them, the share of arable farmland ends up at two thirds of the entire agricultural land of the peninsula. Our assessment demonstrates the possible ecological impacts of such land use change. The results show that the pattern of agricultural land conversion has a great influence on the ornithological species composition in this area. It is our intention to raise the awareness about the potential implications to the environment that might be caused by political decisions. Therefore, the three scenarios purposefully represent very far-reaching developments. But even though the scenarios appear extreme, they are by no means unrealistic, as they are based on real statements by local interest groups that traditionally have a strong influence on decisions in regional politics in northern Germany.

The main difference between the three scenarios lies in the degree of fragmentation of the remaining grassland patches and their location. A conversion of agricultural land starting along existing roads leads to the highest degree of fragmentation, which potentially reduces the quality of the unconverted grassland as potential breeding habitat for birds. On the other hand, a conversion to arable farmland from east to west leaves intact larger areas of grassland in western Eiderstedt but the value of the bird sanctuary near Kotzenbüll is reduced due to its isolation and large shares of the remaining breeding habitats lie in the vicinity of a major tourist destination, which is likely to lead to considerable anthropogenic disturbances.

The potential environmental impacts of the land use conversion differ depending on the resulting distribution pattern of agricultural land. The ornithological impacts are quantified using the *HaSI* assessment scheme. Such *GIS*-based modeling techniques that rely on rule-based parameter combinations are considered to be effective tools in this context (Powell et al., 2005; Thompson et al., 2004). The *HaSI* scheme is validated using bird abundance maps. The methodology of the *HaSI* assessment has a high accuracy because the *HaSI* values correlate well with the observed breeding pair density data of the selected bird species. In regions with a high *HaSI* the breeding bird density is also highest and a low *HaSI* corresponds to a low breeding pair number. Assuming a time independence of the species-specific breeding bird densities, the potential development in the number of breeding pairs supported by the habitats on Eiderstedt can be evaluated.

The potential decline in breeding pairs is particularly strong for Common Redshank, the species with the lowest abundance to start with (cf. Table 4). In all scenarios, its reduction is above average, making the species highly endangered of extinction in this region if breeding habitats were to be reduced as projected. The more abundant species appear to be slightly more resilient to the altered extent of suitable breeding habitats. Both the Eurasian Oystercatcher and the Northern Lapwing partly offset the reduced habitat availability by increasingly utilizing land area with only marginal suitability for breeding.

However, since the number of breeding pairs of all species assessed is reduced drastically in all three scenarios, it can be deduced that the overall quality of the Eiderstedt peninsula as habitat for meadowbirds deteriorates considerably. The main reasons are the increasing isolation of suitable breeding areas and the increasing likelihood of disturbances by anthropogenic activities. The results indicate that not even the declaration of the three bird sanctuaries on Eiderstedt can offset this development since the suitability of these areas as breeding habitat is also critically impaired owing to the land conversions in the neighborhood of these protected sites. Therefore, buffer zones around these bird conservation areas are of paramount importance to preserve the existing habitat quality.

The same holds for the salt marshes outside the main dikes, where the highest bird densities are generally observed. For these areas, suitable conditions for breeding need to be present in the adjacent hinterland as well if their overall quality as ornithological habitat is to be maintained. The importance of an intact neighborhood is augmented if the impacts of sea level rise on the salt marshes are considered as well. Because of impossibility of retreat due to anthropogenic infrastructure such as dikes, an accentuated erosion of the salt marshes might take place, leading to the deterioration or complete loss of the potentially most valuable breeding areas for meadowbirds. The hinterland on the Eiderstedt peninsula could serve as highly suitable substitution habitat, but only if current conditions are preserved.

Based on the results of this assessment, it is possible to identify the characteristics of an optimal bird conservation area on this peninsula, considering not only the habitat suitability for bird species, but also respecting the recent and future socio-economic developments of the local actors via participatory analyses. This study serves as a starting point for such assessments as it provides a model to analyze the potential impacts of land use changes. Moreover, the utilization of scenarios as presented here can help improve the efficiency of integrated land use planning and conservation management of landscapes. By considering potential landscape developments, such scenarios allow the formulation of optimal targets for a given region.

The scenario analysis illustrates that a much smaller number of breeding birds will be supported by the remaining suitable habitats if land use changes occur as projected. Today, many farmers argue that a distinct expansion of arable farming is the only way to survive economically and that shifts in the overall structure of the regional agriculture necessitate these conversions. However, the Eiderstedt peninsula is not only an agricultural region but also a famous tourist destination because of its vast grassland areas and high densities of breeding or migrating birds. It is likely that large-scale conversions of grassland to arable farmland also have an influence on the appearance of the Eiderstedt landscape to visitors. An assessment of the impacts of land use change on tourist activities on Eiderstedt is beyond the scope of this analysis and will be conducted in a separate study. Future assessments of land use change on Eiderstedt will further enhance the understanding of the impacts of planned land conversions, so that hopefully, farmers, birds, and tourists will all find or retain their optimal niches on Eiderstedt in the next decades without having to experience too extensive economic and ecological losses.

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References

Bastian, O. (1997). Gedanken zur Bewertung von Landschaftsfunktionen—Unter besonderer Berücksichtigung der Habitatfunktion. In O. Bastian, & U. Schreiber (Eds.), *NNA-Berichte*, 3 (pp. 106–125). Schneverdingen, Germany [in German].

Bastian, O., & Schreiber, K.-F. (Eds.) (1999). *Analyse und ökologische Bewertung der Landschaft* (2nd ed.). Heidelberg, Germany: Spektrum Akademischer Verlag [in German].

Bauer, P. (1997). *Die Brutvögel Mitteleuropas: Bestand und Gefährdung* (2nd ed.). Wiesbaden, Germany: AULA-Verlag [in German].

Bauer, H. G., Berthold, P., Boye, P., Knief, W., Südbeck, P., & Witt, K. (2002). Rote Liste der Brutvögel Deutschlands, 3. Überarbeitete Fassung. *Berichte zum Vogelschutz, 39*, 13–60 [in German].

Bayliss, J. L., Simonite, V., & Thompson, S. (2005). The use of probabilistic habitat suitability models for biodiversity action planning. *Agriculture, Ecosystems and Environment*, *108*, 228–250.

Beintema, A. J. (1983). Meadow birds as indicators. *Environmental Monitoring and Assessment*, *3*, 391–398.

Cabeza, M., Araújo, M. B., Wilson, R. J., Thomas, C. D., Cowley, M. J. R., & Moilanen, A. (2004). Combining probabilities of occurrence with spatial reserve design. *Journal of Applied Ecology*, *41*(2), 252–262.

European Environment Agency. (EEA) (Ed.) (2004). *EEA Signals 2004*. Copenhagen. 〈http://www.eea.eu.int〉.

Feddersen, F. (1853). *Beschreibung der Landschaft Eiderstedt*. Tönning/Altona, Germany: Schlüter Verlag [in German].

Fischer, L. (Ed.) (1997). *Kulturlandschaft Nordseemarschen*. Bredstedt/Westerhever, Germany: Nordfriisk Instituut [in German].

Gillmor, R., Hillcoat, B., Roselaar, C. S., Vincent, D., Wallace, D. I. M., Wilson, M. G., et al. (1998). *The birds of the Western Palearctic* (vol. 1), *Non-Passerines* (vol. 2): Passerines. Oxford, UK: Oxford University Press.

Granadeiro, J. P., Andrade, J., & Palmeirim, J. M. (2004). Modelling the distribution of shorebirds in estuarine areas using generalised additive models. *Journal of Sea Research*, *52*, 227–240.

Gruber, S. (2006). *Habitatstrukturen in Nahrungsrevieren jungeführender Kiebitze (Vanellus vanellus L.) und deren Einfluss auf die Reproduktion*. Kiel, Germany: Dissertation Christian-Albrechts-Universität zu Kiel [in German].

Guisan, A., Edwards, T. C., Jr., & Hastie, T. (2002). Generalized linear and generalized additive models in studies of species distributions: Setting the scene. *Ecological Modelling*, *157*, 89–100.

Gustafson, E. J., & Parker, G. (1992). Using an index of habitat patch proximity for landscape design. *Landscape and Urban Planning*, *29*, 117–130.

Hammerich, H. (1984). *Eiderstedts Landwirtschaft—Gestern und heute*. Husum, Germany: Husum Druck- und Verlagsgesellschaft [in German].

Hawths Analysis Tools. (2006). 〈http://www.spatialecology.com/htools〉.

Hoffmann, J. (2006). *Schlupferfolgskontrolle von Wiesenlimikolen im Naturraum Eiderstedt*. Trier, Germany: Diplomarbeit Biogeographie Universität Trier [in German].

Hötker, H., Köster, H., & Thomsen, K. M. (2005). Wiesenvögel auf Eiderstedt und in der Eider-Treene-Sorge Niederung/Schleswig-Holstein im Jahre 2001. *Corax, 20*, 1–17 [in German].

Husumer Nachrichten. (2006). *Gemeindevertretersitzung der Gemeinde Osterhever*. Article published March 14, 2006. Husum, Germany [in German].

InfoNet Umwelt. (2007). 〈http://www.umwelt.schleswig-holstein.de〉 (last visited June 25, 2007).

Kiel, S., & Albrecht, K. (2004). Großräumige Landschaftsbewertung mit landscape metrics im Praxistest—Ein Methodenvergleich. In J. Strobl, T. Blaschke, & G. Griesebebner (Eds.), *Angewandte Geoinformatik 2004*. Heidelberg, Germany: Herbert Wichmann Verlag [in German].

Knief, W., Berndt, R. K., Gall, T., Hälterlein, B., Koop, B., & Struwe-Juhl, B. (1995). *Die Brutvögel Schleswig-Holsteins—Rote Liste*. Kiel, Germany: Landesamt für Naturschutz und Landschaftspflege Kiel [in German].

Landesamt für Naturschutz und Landschaftspflege Schleswig-Holstein (LANL). (1993). *Landesweite Biotopkartierung—Kreis Nordfriesland*. Kiel, Germany [in German].

Landesvermessungsamt Schleswig-Holstein (LVermA-SH). (2007a). Digitale Topographische Karte 1:25000—Vorläufige Ausgabe (DTK25-V) of the Preußische Landesaufnahme 1878, pp. 1518, 1519, 1617–1619, 1717–1719.

Landesvermessungsamt Schleswig-Holstein (LVermA-SH). (2007b). Digitale Topographische Karte 1:25000—Vorläufige Ausgabe (DTK25-V) of 2002, pp. 1518, 1519, 1617–1619, 1717–1719.

Lang, S., & Blaschke, T. (2007). *Landschaftsanalyse mit GIS*. Stuttgart, Germany: Ulmer Verlag [in German].

Lang, S., & Tiede, D. (2003). *V-Late extension für ArcGIS—Vektorbasiertes tool zur quantitativen Landschaftsstrukturanalyse. ESRI Anwenderkonferenz 2003 Innsbruck*. Innsbruck, Austria: ESRI [CD-ROM, in German].

Link, P. M., & Schleupner, C. (2007). Agricultural land use changes in Eiderstedt: Historic developments and future plans. *Coastline Reports*, *9*, 197–206.

Manel, S., Dias, J.-M., & Ormerod, S. J. (1999). Comparing discriminant analysis, neural networks and logistic regression for predicting species distributions: A case study with a Himalayan river bird. *Ecological Modelling*, *120*, 337–347.

Meier, D. (2001). *Landschaftsentwicklung und Siedlungsgeschichte des Eiderstedter und Dithmarscher Küstengebietes als Teilregion des Nordseeküstenraumes, Teil 1 und 2*. Bonn, Germany: Habelt Verlag [in German].

Morrison, M. L., Marcot, B. G., & Mannan, R. W. (1992). *Wildlife–habitat relationships: Concepts and applications*. Madison, WI: University of Wisconsin Press.

Naturschutzbund Deutschland (NABU). (2004). Resolution NABU Landesvertreterversammlung: Eiderstedts Grünland muss erhalten bleiben! 〈http://www.nabu.de〉 (last visited June 15, 2007) [in German].

Newton, I. (2003). *The speciation and biogeography of birds*. London, UK: Academic Press.

Powell, M., Accad, A., & Shapcott, A. (2005). Geographic information system (GIS) predictions of past, present habitat distribution and areas for re-introduction of the endangered subtropical rainforest shrub *Triunia robusta* (*Proteaceae*) from south-east Queensland Australia. *Biological Conservation*, *123*, 165–175.

Schlüter, H. (1987). Der Natürlichkeitsgrad der Vegetation als Kriterium der ökologischen Stabilität der Landschaft. In A. Miyawaki (Ed.), *Vegetation ecology and creation of new environments* (pp. 93–102). Tokyo, Japan: Tokai University Press [in German].

Seoane, J., Bustamante, J., & Díaz-Delgado, R. (2004). Competing roles for landscape, vegetation, topography and climate in predictive models of bird distribution. *Ecological Modelling*, *171*, 209–222.

Statistisches Amt für Hamburg und Schleswig-Holstein (Stat A Nord). (1950–2004). Statistische Berichte zur Landwirtschaft in Schleswig-Holstein auf Gemeindeebene, multiple volumes. Kiel, Germany [in German].

Thompson, S., Hazel, A., Bailey, N., Bayliss, J., & Lee, J. T. (2004). Identifying potential breeding sites for the stone curlew (*Burhinus oedicnemus*) in the UK. *Journal for Nature Conservation*, *12*, 229–235.

Tiede, D. (2005). *V-Late—Vector-based landscape analysis tools*. 〈http://www.geo.sbg.ac.at/larg/vlate.htm〉.

Weis, M. (2007). Entwicklung von Landschaftsleitbildern für multifunktionale ländliche Räume. Ein landschaftsökologischer Ansatz auf Basis multitemporaler Landnutzungsdaten sowie sozio-ökonomischer Nutzungsszenarien am Beispiel von Hinterzarten im Hochschwarzwald. Freiburg, Germany: Dissertation Universität Freiburg [in German].

Multiple-species conservation planning with different degrees of coordination: Quantifying area requirements using mixed integer programming

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Abstract

Preservation has often been done ad hoc and uncoordinated between regions, and despite increasing conservation efforts, biodiversity loss is still accelerating. Considering land scarcity and demand for alternative uses, efficiency in conservation strongly depends on the efficiency in land allocation. Systematic conservation planning provides tools to identify optimally located priority areas for conservation. Previous studies have applied the set covering problem by minimizing the resources in terms of cost or area for exogenously given conservation targets. We follow and extent this approach by also considering different degrees of coordination in multiple-species conservation planning. We employ a deterministic, spatially differentiated mathematical optimization model. Mixed integer programming is used to represent minimum habitat area thresholds for all included biodiversity features. The model application to European wetland species addresses five different scenarios of coordination in conservation planning, including systematic, political, and biogeographical coordination of planning. Our approach illustrates and quantifies the efficiency of multi-species conservation activities. We show that simultaneous conservation planning for the whole European Union highly enhances area efficiency. Spatial subdivision of planning, however, leads to higher area requirements and less conservation target achievement. The analysis is done for European wetland species but is easily adaptable to other species, biodiversity features, or regions.

Keywords: systematic conservation planning, minimum set problem, set covering problem, representation, persistence, mathematical optimization model, wetland species, Europe

1. Introduction

Preservation has often been done ad hoc and uncoordinated, leading to non-optimal decisions on conservation areas (Pressey 1994;Margules & Pressey 2000;Gonzales et al. 2003). Protected areas are biased towards economically marginal landscapes which leads to severe underrepresentation of species, habitats, and ecosystems (Pressey & Tully 1994;Cowling et al. 2003;Araujo, Lobo, & Moreno 2007). Furthermore, a high fraction of existing reserves is too small to maintain viable populations of wide-ranging species (Pullin 2002;Primack 2006;Boyd et al. 2008). Hence, despite increasing conservation efforts, biodiversity loss is still accelerating (Myers et al. 2000;Baillie, Hilton-Taylor, & Stuart 2004;Mace et al. 2005).

Hoekstra et al. (2005) identified the vast majority of the European continent’s terrestrial area as crisis ecoregions with extensive habitat conversion and limited habitat protection. Protected areas in the European Union under the Natura 2000 network cover currently about 20 percent of the total land area (European Commission 2008). European countries and the European Union apply different strategies of conservation planning. There are protection plans for selected single species (Tucakov et al. 2006;Koffijberg & Schaffer 2006;Amstislavsky et al. 2008), species groups (Papazoglou et al. 2004;Lovari 2004;Goverse et al. 2006) as well as national conservation programs (Sepp et al. 1999;Vuorisalo & Laihonen 2000;Elliott & Udovc 2005). Transfrontier national parks covering features of specific biogeographical regions are located for instance in mountainous regions (Oszlanyi et al. 2004;Williams et al. 2005). Important pan-European initiatives (see Jones-Walters (2007) for a review on European ecological networks) are the Natura 2000 network basing on the Birds and Habitats Directives (79/409/EEC ;92/43/EEC) and the Emerald’s network basing on the Bern convention (Council of Europe 1979).

In light of high economic pressure on land area questions on the efficiency of the mentioned strategies arise. How efficient in terms of area requirement are different strategies of coordination in conservation planning? The main question we address in this study is: What impact does comprehensive spatial coordination in conservation planning have on the overall area requirement for protected areas?

Considering land scarcity and demand for alternative uses, efficiency in conservation strongly depends on efficiency in land allocation. Systematic conservation planning provides tools to identify optimally located priority areas for conservation (Margules & Pressey 2000;Possingham, Ball, & Andelman 2000). The minimum set problem detects how and where to protect as much biodiversity features as possible while minimizing the necessary resources (typically area or cost) for achieving the conservation targets (Possingham, Ball, & Andelman 2000;McDonnell et al. 2002;Williams, ReVelle,

& Levin 2005). Previous studies have optimized the arrangement of protected areas for exogenously given conservation targets (Saetersdal, Line, & Birks 1993;ReVelle, Williams, & Boland 2002;Tognelli, de Arellano, & Marquet 2008).
Several studies pointed out that the focus in reserve site selection lies on representation of biodiversity features whereas persistence is often inadequately addressed (Cabeza & Moilanen 2001;Önal & Briers 2005;Williams, ReVelle, & Levin 2005;Haight & Travis 2008). We follow and extend the minimum set problem by attaching the same value to both representation and persistence. As comparably proposed by Marianov, ReVelle, & Snyder (2008), we account for species-specific habitat area needs to enable viable populations.

Setting definitive and measurable conservation targets has been discussed controversially (Soulé & Sanjayan 1998;Tear et al. 2005;Wilhere 2008). We do not determine a single representation target as sufficient for the long-term protection of the considered biodiversity features, but rather show the influence of stepwise increasing representation targets on the overall area requirement. Justus, Fuller, & Sarkar (2008) adopt a similar approach for representing biodiversity surrogates in five regions.

Multiple-species conservation planning has been discussed elaborately elsewhere (Moilanen et al. 2005;Nicholson & Possingham 2006;McCarthy, Thompson, & Williams 2006). However, most previous studies have neither explicitly examined different degrees of multiple-species conservation planning nor quantified the area reduction potential resulting from comprehensive coordination. First studies on the impact of different spatial extents in planning provide Vazquez, Rodriguez, & Arita (2008) and Pearce et al. (2008) for North America.

We employ a deterministic, spatially explicit mathematical optimization model, which allocates species habitats by minimizing the total area for setting aside land for conservation purposes. Whether to prefer iterative heuristics or exact algorithms in reserve selection has been covered extensively (Pressey, Possingham, & Margules 1996;Rosing, ReVelle, & Williams 2002;Vanderkam, Wiersma, & King 2007). Due to their advantage of guaranteed optimality, we employ integer programming techniques. Our model quantifies area requirements for conservation under different assumptions of coordinated planning. We apply scenarios that refer to commonly used conservation strategies in Europe and globally. The analysis is done for European wetland species but is easily adaptable to other species, biodiversity features, or regions.

2. Methods

Planning units

We use a spatially explicit model based on planning units that may differ in shape and size. The maximum available habitat area to be selected can be determined for each planning unit. Supposable options are either to use the total planning unit area, a fraction of the planning unit, or real or modelled data on potential reserve areas per planning unit.

There are two possible initial states of each planning unit; it is either occupied by a species (1) or not (0). We assume that each planning unit occupied by a species is equally appropriate for that species.

If a species' area requirement cannot be fulfilled within a single planning unit, we allow the model to choose further habitat area in adjacent planning units.

Conservation targets: integrating representation and persistence

To make conservation effort reasonable, both representation and persistence of biodiversity features have to be secured (Margules & Pressey 2000;Sarkar et al. 2006).

Each species has to reach pre-assigned representation targets in our model. We can either apply same representation targets for each species or determine species-specific targets.

We assume the persistence criterion to be fulfilled when two conditions are met. First, a species has to be able to form at least one viable population each time it is represented. A population is considered as viable when the allocated land area equals smallest the minimum critical area which is defined as follows:

minimum critical area = density * minimum viable population size for all species

This minimum critical area is a species-specific measure based on density data and assumptions on minimum viable population sizes. Density data can differ substantially depending on habitat quality (Foppen, Chardon, & Liefveld 2000;Riley 2002) or due to bias in sampling effort (Schwanghart, Beck, & Kuhn 2008). To account for that variability, we enable to solve the model for different density data. We assume furthermore that no species are mutually exclusive or affect each other in terms of density.

The second condition for the persistence criterion refers to habitat type requirements. We assume that each species requires specific habitat types which can be either necessary for the species' survival or optional habitats. Thus, the land area determined by the minimum critical area has to be allocated to the habitat types required by the relevant species.

Mathematical optimization model

The formal framework used here follows and expands the set covering problem. We use the following notation: $p = (1,\ldots,N)$ is the set of planning units; $h = (1,\ldots,N)$ is the set of habitat types; $q = (1,\ldots,N)$ is the set of different habitat qualities. The objective variable $y_{p,h,q}$ represents the total habitat area in hectares. $s = (1,\ldots,N)$ is the set of species. $x_{s,p}$ is a binary variable with $x_{s,p} = 1$ indicating species s is chosen in planning unit p, and $x_{s,p} = 0$ otherwise. $area_{p,h}$ is the maximum available area to be selected per planning unit p and habitat type h. $density_{s,q}$ represents species- and habitat quality-specific density data. $popsize_s$ is a species-specific proxy for minimum viable population size. $habitattype_s$ displays the required habitat types per species s. rt_s is the representation target per species s. If a species occurs less than the representation target, $rtdeficit_s$ allows a deviation from the target.

Minimize $\sum_{p,h} y_{p,h,q}$ for all q, [1]

subject to:

$$\sum_{q} y_{p,h,q} \leq area_{p,h} \quad \text{for all p,h} \quad [2]$$

$$\sum_{h,q} density_{s,q} * y_{p,h,q} \geq popsize_s * x_{s,p} \quad \text{for all p,s,} \quad [3]$$

$$\sum_{q} y_{c,h,q} \geq habitattype_s * x_{s,c} \quad \text{for all p,h,s,} \quad [4]$$

$$\sum_{p} x_{s,p} \geq rt_s - rtdeficit_s \quad \text{for all s,} \quad [5]$$

$$\sum_{p,h,q} density_{s,q} * y_{p,h,q} \geq rt_s * popsize_s \quad \text{for all s,} \quad [6]$$

The objective function [1] is to minimize the overall habitat area. Constraint [2] limits the selectable area per planning unit. Constraint [3] ensures that the selected area per planning unit is at least large enough to support a minimum viable population of each species which is chosen in a particular planning unit. Constraint [4] controls that the required habitat types are allocated to each species which is chosen in a particular planning unit. Constraint [5] enforces a given representation target for all species. It allows a deviation from the target if the number of occurrences of a species is less than the representation target. Constraint [6] ensures that the total population size equals at least the representation target times the minimum viable population size.

The problem is solved with mixed integer programming (MIP) using the general algebraic modelling system (GAMS 22.7).

3. Application to European wetland biodiversity

Freshwater wetlands are of outstanding importance for biodiversity conservation (Mitsch & Gosselink 1993;Schweiger et al. 2002;Bobbink et al. 2006). They also play prominent roles in carbon storage (Belyea & Malmer 2004;Zhou, Wang, & Li 2007) and provision of water-related ecosystem services (Brauman et al. 2007). However, wetlands are severely threatened by human disturbances (Bronmark & Hansson 2002;Bobbink, Beltman, Verhoeven, & Whigham 2006). Due to their relevance for conservation and related environmental objectives, we apply our model to freshwater wetland habitats.

Species assemblage and occurrence data

Freshwater wetland dependent species serve as surrogates for biodiversity. 70 tetrapod species listed in the Appendixes of the birds and the habitats directive (79/409/EEC ;92/43/EEC) depend on freshwater wetland habitats, comprising 16 amphibian, 4 reptile, 41 breeding bird, and 9 mammal species (see Appendix: Table 1).

Recorded occurrences from species' atlases represent the species' current distribution in Europe. These data originate from the Atlas of amphibians and reptiles in Europe (Gasc et al. 1997), The EBCC Atlas of European Breeding Birds (Hagemeijer & Blair 1997), and The Atlas of European Mammals (Mitchell-Jones et al. 1999).

Density data and proxies for minimum viable population sizes

Density data for the 70 species were compiled through extensive literature review; we use the maximum observed density (see Appendix: Table 2). The proxies for minimum viable population sizes (see Appendix: Table 2) base on Verboom et al. (2001). We adapted their proposed standards for minimum population sizes depending on species' body sizes and life expectancy. One viable population in our model represents 120 reproductive units (pairs/territories/families; depending on species group) of long lived/large vertebrates and 200 reproductive units of middle-long lived/medium sized and short-lived/small vertebrates respectively.

Habitat type requirements

Data on habitat type requirements result from literature review. We include five broad wetland habitat types in our dataset, namely mire, wet forest, wet grassland, water course, and water body. A further type "open water" is applied to species that either require water courses or water bodies. See Appendix (Table 3) for the required and optional habitat types for the 70 wetland species.

Spatial scope and planning units

The dataset comprises the European Union with 25 out of 27 member states (see Figure 1). Cyprus was excluded from the analysis due to the lack of comprehensive atlas data of all species; Malta was excluded as none of the considered species was recorded there in the used data sources. Macaronesia is furthermore excluded due to data deficiencies.

Fig. 1: Spatial scope of empirical model application

The planning units base on the resolution of the available occurrence data of the species. The atlases use the Universal Transverse Mercator (UTM) projection with grid squares of about 50 km edge length. We use only those parts of the grid cells covering land area of the considered European countries as planning units. In this model version we allow to allocate the whole unsealed land area of each planning unit to the five relevant habitat types. The European Union dataset contains 2235 planning units.

Scenarios of Coordination

We define coordination as solving the set covering problem for several species simultaneously. We distinguish between five broad categories of coordination. The model minimizes the area requirement for each particular assemblage of species jointly.

There are two reference scenarios delineating the lower and upper boundaries of possible solutions for scenarios without spatial segregation of planning within the European Union. One assumes that each of the considered 70 species is treated independently. In this scenario there is no coordination in planning, we have **individual conservation planning**. The second scenario displays the case of **completely coordinated conservation planning**. This most ideal scenario represents the maximum possible simultaneous conservation within our application. We assume completely coordinated planning for all relevant species here.

We then execute three model scenarios to simulate area requirements of political, biogeographical, and systematic coordination in conservation planning. Political and biogeographical coordination implies dividing the European Union into sub-units.

In the first scenario we apply **coordinated conservation planning within countries**. Each European state protects all species which occurring in large parts on its territory (see Appendix: Table 4a), thus we have a political division of planning. Within the borders of each country the conservation planning is coordinated, the species are conserved simultaneously.

A further scenario looks at spatially coordinated conservation effort in each European biogeographical region. Individual conservation planning for seven biogeographical units encompassing the European Union (alpine, atlantic, black sea, boreal, continental, mediterranean, pannonian) simulates **coordinated conservation planning within biogeographical regions** (see Appendix: Table 4b).

In the next scenario we systematically separate the species into tetrapod classes. We consider the four taxon groups amphibians, reptiles, birds, and mammals as entities for each of which individual plans are developed. Those model runs provide estimations on area requirement for **coordinated conservation planning within taxonomic groups** on the whole spatial extent.

4. Results

The habitat allocation model minimizes total area for habitat protection for different conservation targets. Figure 2 shows the allocation to the wetland habitat types as well as the total area from model runs with 70 species. The area is shown in million hectares for conservation targets from 1 to 25. Each single conservation target ensures that each species has enough land on required habitat types to form at least one viable population in a location where it actually occurs. We assume here that conservation activities are entirely harmonised. Different species are conserved simultaneously, the planning is completely coordinated within the European Union.

Figure 3 compares the total area requirements for all five scenarios of coordination graphically. Computing the two scenarios with subdivision of the total area into countries or biogeographical regions results in the highest total area requirement. Among the three scenarios covering the whole spatial extent at once, the complete coordination yields by far the least area demand. For the same conservation target several millions of hectares less are possible when coordinating planning comprehensively.

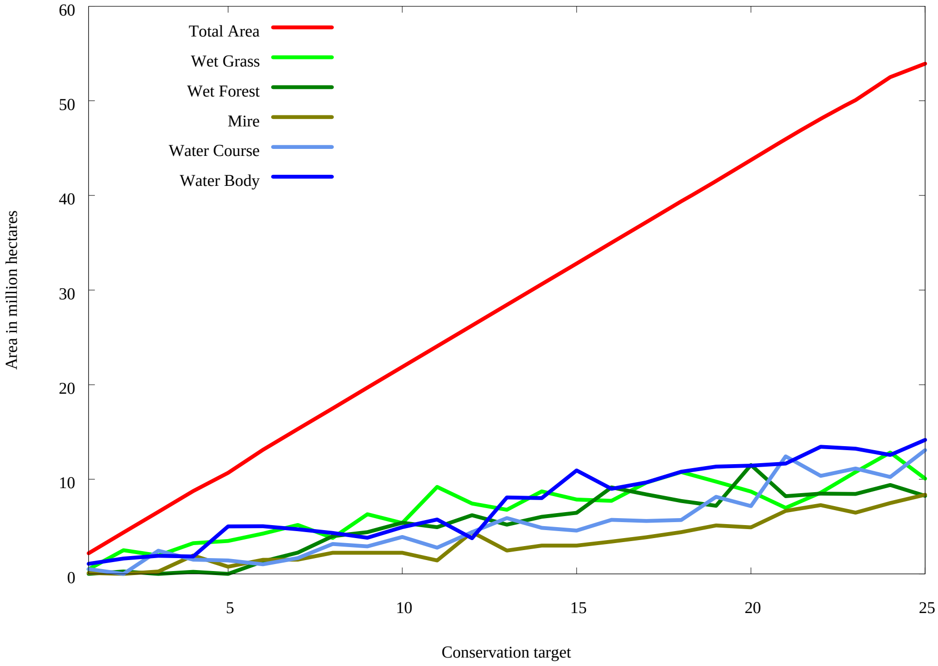

Fig. 2: Completely coordinated conservation planning: allocation to wetland habitat types and total area requirement

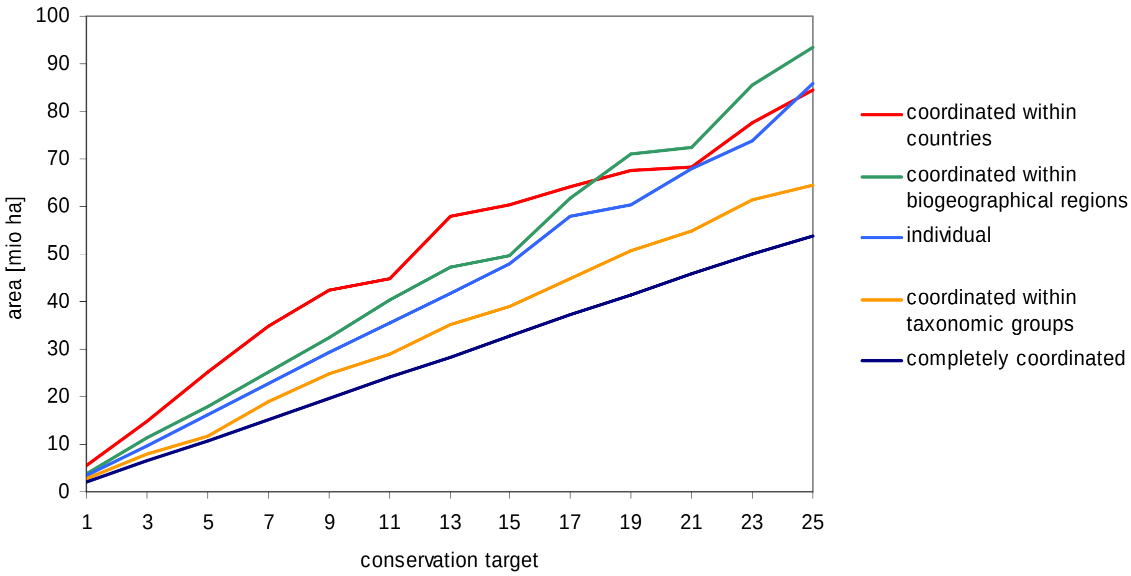

Fig. 3: Total area requirements for five scenarios of coordinated conservation planning

Table 1 displays major results for conservation targets 1, 10, and 20. Note that the maximum numbers of species covered per planning unit in the two spatially separated scenarios are similar to or even higher than in three spatially all-embracing scenarios. However, their average number of species per planning unit is lower throughout the targets.

Table 1: Key results of scenarios of coordination for conservation targets 1, 10, and 20

	Degree of coordination in conservation planning														
	coordinated within countries			coordinated within biogeographical regions			individual			coordinated within taxonomic groups			completely coordinated		
conservation target	1	10	20	1	10	20	1	10	20	1	10	20	1	10	20
selected planning units (n=1996)	159	552	699	162	586	932	49	340	657	113	367	581	62	304	484
covered species (n=70) per planning unit															
average	2	3	3	2	3	3	3	4	4	3	4	4	3	4	4
maximum	18	25	25	11	18	18	18	23	24	19	21	26	15	18	19
total area [mio ha]	5.0	44.6	68.4	3.8	35.9	73.2	3.5	36.2	63.5	2.6	26.1	51.9	2.2	21.9	43.7

Target achievement differs substantially between scenarios (see Table 2). The higher the conservation target in the country- and region-scenario, the less species are able to fulfill it. On the other hand do many species exceed the target up to 200 and 300 % or even more. This bipolarity is not evident in the three other scenarios. All species meet their conservation targets. A majority of them is represented exactly according to the respective target.

Figure 4 shows the spatial distribution of selected planning units for all five scenarios exemplarily for conservation target 5.

Table 2: Performance of scenarios in conservation target achievement

	Degree of coordination in conservation planning														
	coordinated within countries			coordinated within biogeographical regions			individual			coordinated within taxonomic groups			completely coordinated		
conservation target	1	10	20	1	10	20	1	10	20	1	10	20	1	10	20
number of species (n=70) fulfilling conservation target															
< 100%	2	10	32	2	11	15									
100%	**29**	**22**	**12**	**26**	**21**	**18**	**53**	**34**	**35**	**47**	**39**	**39**	**61**	**65**	**63**
< 200%		8	19	2	8	15		18	19		19	18	6	4	7
< 300%	26	25	5	29	29	17	10	10	9	6	5	7	3		
> 300%	13	5	2	11	1	5	7	8	7	17	7	6		1	

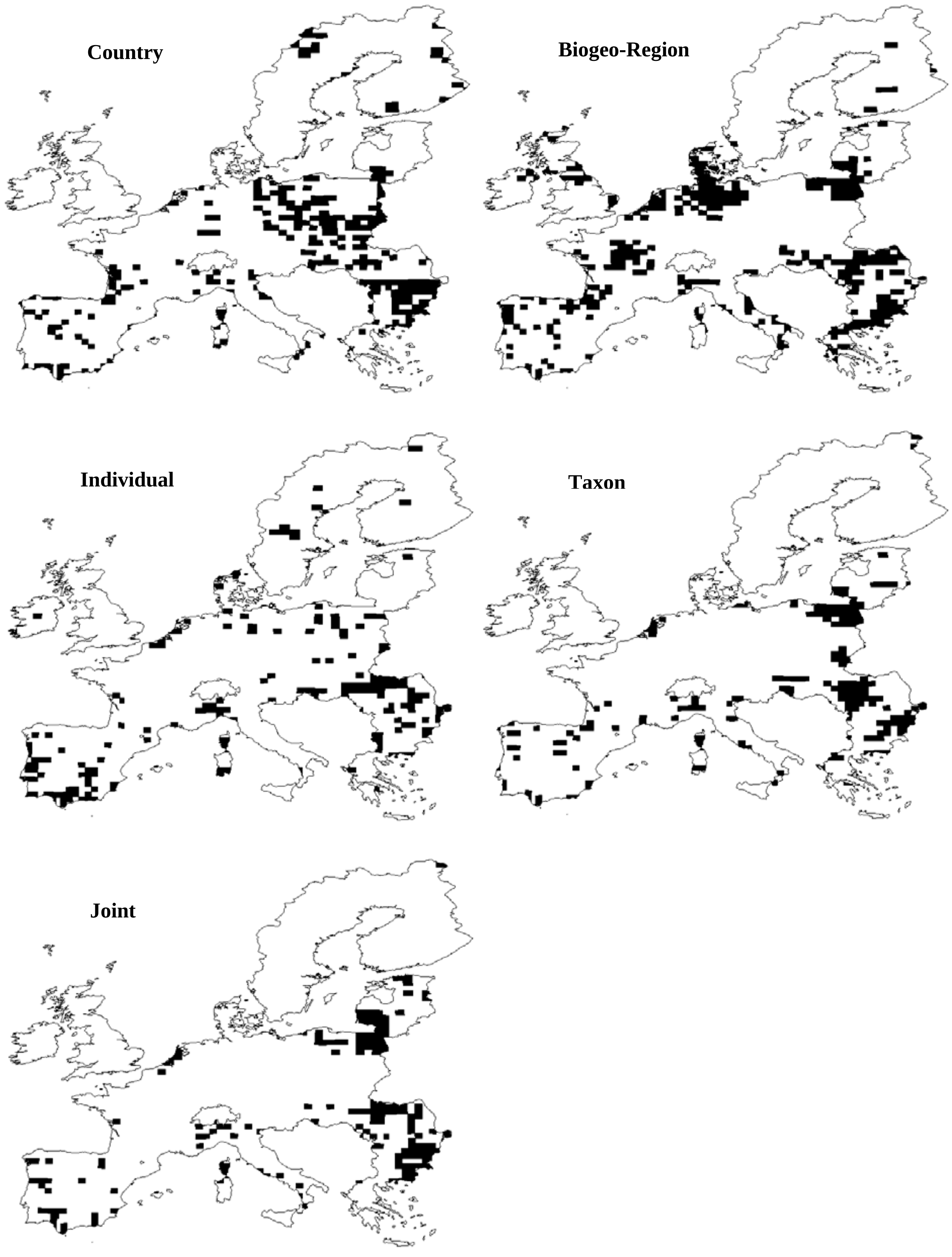

Fig. 4: Spatial distribution of selected planning units for conservation target 5

5. Discussion

Efficiency of multiple-species conservation planning

Our approach illustrates and quantifies the efficiency of multi-species conservation activities. For the case of 70 tetrapod species of European conservation concern completely simultaneous planning results in a substantial decrease in area requirement compared to several conservation planning exercises for the same species assemblage but different degrees of coordination.

Our results indicate that conservation planning should take place at the largest possible spatial scale. Subdividing our planning scope, the European Union, into seven biogeographical regions or even into single countries leads to higher overall area requirement as well as less target achievement of the conservation features. Applying different degrees of multiple-species conservation planning on the whole planning region does still yield different area demands, but on a lower level and with no problems in target achievement. We showed that the spatial extent of planning can have serious effect on locations and extent of priority areas for conservation. See Vazquez et al. (2008) for similar findings for North America.

Our plan for the country-wide coordination results in the least target achievement whereas needing the highest amount of habitat area. This is not to question the assignment of national responsibilities for species (see Schmeller et al. (2008) for a review). Yet, according to our results, options for cooperation beyond the borders of countries should be examined whenever reasonable. The same argumentation holds for conservation planning within differing biogeographical regions.

Simplifications in conservation planning

Applying the minimum set problem usually necessitates several simplifications. First of all, species are taken as surrogates for biodiversity what may lead to non-optimal decisions (Margules & Pressey 2000;Rodrigues & Brooks 2007). The necessity to include occurrence data as basic input parameter into reserve selection models leads to bias towards well-surveyed species such as vertebrates (Polasky, Camm, & Garber-Yonts 2001;Kerley et al. 2003;Hazen & Harris 2007). We furthermore assume that species do not interact, e.g. do not influence each others' densities, and treat each colonized planning unit as equally appropriate for a species.

In addition to these general shortcuts, two further simplifications were made. First, we do not directly account for spatial reserve design criterions like connectivity or compactness in our model. Even so, simultaneous planning implicitly results in compact reserves. Second, we did not include existing wetland habitats but rather allowed the model to allocate the whole unsealed land area to the wetland habitat types which can lead to unrealistic high wetland fractions. Though, as not every species would need essentially 100 % of its habitat to be wetland, the total area required for wetland species protection is a more significant result parameter than the shares of different habitat types. However, first results from model runs with modelled data on the extent of existing and convertible wetlands in Europe from Schleupner (2007) indicate that the range of results does not change markedly.

What about the costs? Reduced area requirement for reservation does not guarantee reduced costs for achieving the respective land (Balmford et al. 2000;Polasky, Camm, & Garber-Yonts 2001;Naidoo et al. 2006). Cost is an important factor not directly accounted for in our study as we minimize the overall habitat area instead of the land costs. Yet, when appropriate data on land costs are not available, conservation planning studies often use area as a substitute for costs (McDonnell, Possingham, Ball, & Cousins 2002).

Conservation target: integrating representation and persistence

Each step of the conservation target does not only correspond to the respective representation of a biodiversity feature, but rather to the representation of a viable occurrence of it. Unlike commonly done in conservation planning (Williams & Araujo 2002;Williams, ReVelle, & Levin 2005;Tognelli, de Arellano, & Marquet 2008), not the whole planning unit is selected as a priority area for conservation in any case. The identified area per planning unit rather equals the minimum critical area per species and thus may be less than the total planning unit's area. In case a species' area requirement for a viable population cannot be fulfilled within a single planning unit, area of adjacent planning units is added. This procedure seems reasonable when dealing with large planning units for which it is unlikely or even unfeasible to entirely reserve them. Such a situation arises for example when using species occurrence data with coarse resolution resulting in planning units with an edge length of about 50 kilometers in our case. Note that we do not account for spatio-temporal aspects of persistence.

We made several simplifications to adopt the conservation target approach. First, though the model structure allows determining species-specific representation targets, we demand the same target for each species in our application. Main reason for it is the difficulty in consistently determining explicit targets for individual species (Kerley, Pressey, Cowling, Boshoff, & Sims-Castley 2003). Second, to account for persistence, reliable density data as well as proxies for minimum viable population sizes are essential. Yet, density data from literature may vary substantially between sources or be biased towards regions with high population densities (Schwanghart et al. 2008). Whether using absolute numbers for viable population sizes seems appropriate is further subject of extensive discussion (Nicholson et al. 2006;Traill, Bradshaw, & Brook 2007). Note that we do not assume the utilized figures represent real minimum viable populations nor that defining explicit sizes for persistent populations is possible. This is particularly true for such a range of species with divergent habitat requirements. Given the lack of better data, we still use these figures as working targets in our conservation planning exercise. Similar proceeding can be found in Kautz & Cox (2001), Verboom et al. (2001), and Kerley (2003).

Reality in conservation planning is undoubtedly much more complex than displayed in our habitat allocation model. However, with this simplified construction we gain valuable insights into the substantial differences of area demand and target achievement that common strategies in multiple-species conservation planning involve.

6. Implications for conservation planning

Simultaneous conservation planning highly enhances area efficiency. However, we show a simplified case study delineating maximum possible advantages from multiple-species conservation planning in terms of area requirements. An application of this approach still demands great skill in ensuring adequate provision for each species' specific needs. Encouraging to imprudently lump together basically different species is not purpose of this study as such proceeding will most likely not favour conservation success.

How much coordination and in which cases?

Completely coordinated conservation implies a high degree of collaboration between different organizations and thus likely great effort with respect to time and costs. On the other hand does developing and maintaining a large number of separated protection plans for particular or several species not necessarily correlate with less effort. Our results show that even small degrees of coordination can lead to substantial benefits from synergy effects. Thus, actually some coordination is basically preferable to none. Our findings show furthermore that spatial segregation of planning is not advisable as it may result in non-optimal decision-making. To get the highest benefits for species protection from systematic conservation planning tools, planning should be applied on the largest spatial extent possible.

Nevertheless, in certain circumstances coordination in planning may not be the best option for action. In particular cases, e.g. when species are directly faced with extinction, urgent action is indispensable. Hence, time lags until reserve establishment associated with comprehensive planning would discourage coordination efforts in such cases.

Highly coordinated conservation planning seems particular suitable in cases where on large spatial extent new reserve systems are to be established or current systems are to be enlarged.

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References

79/409/EEC. Council Directive of 2 April 1979 on the conservation of wild birds. 4-2-1979.

92/43/EEC. Council Directive of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. 5-21-1992.

Amstislavsky, S., Lindeberg, H., Aalto, J., & Kennedy, M. W. 2008. Conservation of the European Mink (Mustela lutreola): Focus on Reproduction and Reproductive Technologies. Reproduction in Domestic Animals

Araujo, M. B., Lobo, J. M., & Moreno, J. C. 2007. The Effectiveness of Iberian Protected Areas in Conserving Terrestrial Biodiversity. Conservation Biology 21, 1423-1432.

Baillie, J. E. M., Hilton-Taylor, C., & Stuart, S. N. 2004. *IUCN Red List of Threatened Species: A Global Species Assessment* IUCN, Gland (Switzerland).

Balmford, A., Gaston, K. J., Rodrigues, A. S. L., & James, A. 2000. Integrating costs of conservation into international priority setting. Conservation Biology 14, 597-605.

Belyea, L. R. & Malmer, N. 2004. Carbon sequestration in peatland: patterns and mechanisms of response to climate change. Global Change Biology 10, 1043-1052.

Bobbink, R., Beltman, B., Verhoeven, J. T. A., & Whigham, D. F. 2006. *Wetlands: Functioning, Biodiversity Conservation, and Restoration*, 1 edn. Springer, Berlin.

Boyd, C., Brooks, T. M., Butchart, S. H. M., Edgar, G. J., da Fonseca, G. A. B., Hawkins, F., Hoffmann, M., Sechrest, W., Stuart, S. N., & van Dijk, P. P. 2008. Spatial scale and the conservation of threatened species. Conservation Letters 1, 37-43.

Brauman, K. A., Daily, G. C., Duarte, T. K., & Mooney, H. A. 2007. The Nature and Value of Ecosystem Services: An Overview Highlighting Hydrologic Services. Annual Review of Environment and Resources 32, 67-98.

Bronmark, C. & Hansson, L. A. 2002. Environmental issues in lakes and ponds: current state and perspectives. Environmental Conservation 29, 290-307.

Cabeza, M. & Moilanen, A. 2001. Design of reserve networks and the persistence of biodiversity. Trends in Ecology & Evolution 16, 242-248.

Council of Europe. Convention on the conservation of European Wildlife and Natural Habitats. 1979.

Cowling, R. M., Pressey, R. L., Rouget, M., & Lombard, A. T. 2003. A conservation plan for a global biodiversity hotspot - the Cape Floristic Region, South Africa. Biological Conservation 112, 191-216.

Elliott, C. & Udovc, A. 2005. Nature conservation and spatial planning in Slovenia: continuity transition. Land Use Policy 22, 265-276.

European Commission 2008, *Natura 2000 European Commission DG ENV Newsletter* 24.

Foppen, R. P. B., Chardon, J. P., & Liefveld, W. 2000. Understanding the role of sink patches in source-sink metapopulations: Reed Warbler in an agricultural landscape. Conservation Biology 14, 1881-1892.

Gasc, J. P., Cabela, A., Crnobrnja-Isailovic, J., Dolmen, D., Grossenbacher, K., Haffner, P., Lescure, J., Martens, H., Martínez Rica, J. P., Maurin, H., Oliveira, M. E., Sofiandou, T. S., Veith, M., & Zuiderwijk, A. 1997. *Atlas of amphibians and reptiles in Europe*, Collection Patrimoines Naturels edn. Societas Europaea Herpetologica, Muséum National d'Histoire Naturelle & Service du Petrimone Naturel, Paris.

Gonzales, E. K., Arcese, P., Schulz, R., & Bunnell, F. L. 2003. Strategic reserve design in the central coast of British Columbia: integrating ecological and industrial goals. Canadian Journal of Forest Research-Revue Canadienne de Recherche Forestiere 33, 2129-2140.

Goverse, E., Smit, G. F. J., Zuiderwijk, A., & van der Meij, T. The national amphibian monitoring program in the Netherlands and NATURA 2000. Vences, M, Köhler, J., Ziegler, T., and Böhme, W. 39-42. 2006. Herpetologica Bonnensis II. Proceedings of the 13th Congress of the Societas Europaea Herpetologica.
Ref Type: Conference Proceeding

Hagemeijer, W. J. M. & Blair, M. J. 1997. *The EBCC Atlas of European Breeding Birds: Their Distribution and Abundance* T & A D Poyser, London.

Haight, R. & Travis, L. 2008. Reserve Design to Maximize Species Persistence. Environmental Modeling and Assessment 13, 243-253.

Hazen, H. D. & Harris, L. M. 2007. Limits of territorially-focused conservation: a critical assessment based on cartographic and geographic approaches. Environmental Conservation 34, 280-290.

Hoekstra, J. M., Boucher, T. M., Ricketts, T. H., & Roberts, C. 2005. Confronting a biome crisis: global disparities of habitat loss and protection. Ecology Letters 8, 23-29.

Jones-Walters, L. 2007. Pan-European Ecological Networks. Journal for Nature Conservation 15, 262-264.

Justus, J., Fuller, T., & Sarkar, S. 2008. Influence of Representation Targets on the Total Area of Conservation-Area Networks. Conservation Biology 22, 673-682.

Kautz, R. S. & Cox, J. A. 2001. Strategic habitats for biodiversity conservation in Florida. Conservation Biology 15, 55-77.

Kerley, G. I. H., Pressey, R. L., Cowling, R. M., Boshoff, A. F., & Sims-Castley, R. 2003. Options for the conservation of large and medium-sized mammals in the Cape Floristic Region hotspot, South Africa. Biological Conservation 112, 169-190.

Koffijberg, K. & Schaffer, N. 2006. International single species action plan for the conservation of the corncrake Crex crex. AEWA Technical Series 9.

Lovari, S. 2004. Survey and conservation of some endangered Italian mammals. Quaderni di Conservazione della Natura 18.

Mace, G. M., Masundire, H., Baillie, J. E. M., Ricketts, T. H., Brooks, T. M., & et al. 2005. Biodiversity. In Ecosystems and human well-being: Current state and trends: Findings of the Condition and Trends Working Group, eds. R. Hassan, R. Scholes, & N. Ash, pp. 77-122. Island Press, Washington (D. C.).

Margules, C. R. & Pressey, R. L. 2000. Systematic conservation planning. Nature 405, 243-253.

Marianov, V., ReVelle, C., & Snyder, S. 2008. Selecting compact habitat reserves for species with differential habitat size needs. Computers & Operations Research 35, 475-487.

McCarthy, M. A., Thompson, C. J., & Williams, N. S. G. 2006. Logic for designing nature reserves for multiple species. American Naturalist 167, 717-727.

McDonnell, M. D., Possingham, H. P., Ball, I. R., & Cousins, E. A. 2002. Mathematical methods for spatially cohesive reserve design. Environmental Modeling & Assessment 7, 107-114.

Mitchell-Jones, A. J., Amori, G., Bogdanowicz, W., Krystufek, B., Reijnders, P. J. H., Spitzenberger, F., Stubbe, M., Thissen, J. B. M., Vohralík, V., & Zima, J. 1999. *The Atlas of European Mammals* Academic Press, London.

Mitsch, W. J. & Gosselink, J. G. 1993. *Wetlands*, 2nd edn. Van Nostrand Reinhold, New York.

Moilanen, A., Franco, A. M. A., Eary, R. I., Fox, R., Wintle, B., & Thomas, C. D. 2005. Prioritizing multiple-use landscapes for conservation: methods for large multi-species planning problems. Proceedings of the Royal Society B-Biological Sciences 272, 1885-1891.

Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B., & Kent, J. 2000. Biodiversity hotspots for conservation priorities. Nature 403, 853-858.

Naidoo, R., Balmford, A., Ferraro, P. J., Polasky, S., Ricketts, T. H., & Rouget, M. 2006. Integrating economic costs into conservation planning. Trends in Ecology & Evolution 21, 681-687.

Nicholson, E. & Possingham, H. P. 2006. Objectives for Multiple-Species Conservation Planning. Conservation Biology 20, 871-881.

Nicholson, E., Westphal, M. I., Frank, K., Rochester, W. A., Pressey, R. L., Lindenmayer, D. B., & POSSINGHAM, H. P. 2006. A new method for conservation planning for the persistence of multiple species. Ecology Letters 9, 1049-1060.

Önal, H. & Briers, R. 2005. Designing a conservation reserve network with minimal fragmentation: A linear integer programming approach. Environmental Modeling and Assessment 10, 193-202.

Oszlanyi, J., Grodzinska, K., Badea, O., & Shparyk, Y. 2004. Nature conservation in Central and Eastern Europe with a special emphasis on the Carpathian Mountains. Environmental Pollution 130, 127-134.

Papazoglou, C., Kreiser, K., Waliczky, Z., & Burfield, I. 2004. *Birds in the European Union: a status assessment* BirdLife International, Cambridge.

Pearce, J. L., Kirk, D. A., Lane, C. P., Mahr, M. H., Walmsley, J., Casey, D., Muir, J. E., Hannon, S., Hansen, A., & Jones, K. 2008. Prioritizing avian conservation areas for the Yellowstone to Yukon Region of North America. Biological Conservation 141, 908-924.

Polasky, S., Camm, J. D., & Garber-Yonts, B. 2001. Selecting Biological Reserves Cost-Effectively: An Application to Terrestrial Vertebrate Conservation in Oregon. Land Economics 77, 68-78.

Possingham, H., Ball, I., & Andelman, S. 2000. Mathematical methods for identifying representative reserve networks. In Quantitative methods for conservation biology, eds. S. Ferson & M. A. Burgman, pp. 291-306. Springer, New York.

Pressey, R. L. 1994. Ad Hoc Reservations - Forward Or Backward Steps in Developing Representative Reserve Systems. Conservation Biology 8, 662-668.

Pressey, R. L., Possingham, H. P., & Margules, C. R. 1996. Optimality in reserve selection algorithms: When does it matter and how much? Biological Conservation 76, 259-267.

Pressey, R. L. & Tully, S. L. 1994. The Cost of Ad Hoc Reservation - A Case-Study in Western New-South-Wales. Australian Journal of Ecology 19, 375-384.

Primack, R. B. 2006. *Essentials of Conservation Biology*, Fourth edn. Sinauer Associates, Sunderland, MA.

Pullin, A. S. 2002. *Conservation Biology* Cambridge University Press, Cambridge.

ReVelle, C. S., Williams, J. C., & Boland, J. J. 2002. Counterpart models in facility location science and reserve selection science. Environmental Modeling & Assessment 7, 71-80.

Riley, J. 2002. Population sizes and the status of endemic and restricted-range bird species on Sangihe Island, Indonesia. Bird Conservation International 12, 53-78.

Rodrigues, A. S. L. & Brooks, T. M. 2007. Shortcuts for biodiversity conservation planning: The effectiveness of surrogates. Annual Review of Ecology Evolution and Systematics 38, 713-737.

Rosing, K. E., ReVelle, C. S., & Williams, J. C. 2002. Maximizing species representation under limited resources: A new and efficient heuristic. Environmental Modeling & Assessment 7, 91-98.

Saetersdal, M., Line, J. M., & Birks, H. J. B. 1993. How to Maximize Biological Diversity in Nature-Reserve Selection - Vascular Plants and Breeding Birds in Deciduous Woodlands, Western Norway. Biological Conservation 66, 131-138.

Sarkar, S., Pressey, R. L., Faith, D. P., Margules, C. R., Fuller, T., Stoms, D. M., Moffett, A., Wilson, K. A., Williams, K. J., Williams, P. H., & Andelman, S. 2006. Biodiversity conservation planning tools: Present status and challenges for the future. Annual Review of Environment and Resources 31, 123-159.

Schleupner, C. 2007, *Estimation of Spatial Wetland Distribution Potentials in Europe*, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg, FNU-135.

Schmeller, D. S., Gruber, B., Budrys, E., Framsted, E., Lengyel, S., & Henle, K. 2008. National Responsibilities in European Species Conservation: a Methodological Review. Conservation Biology 22, 593-601.

Schwanghart, W., Beck, J., & Kuhn, N. 2008. Measuring population densities in a heterogeneous world. Global Ecology and Biogeography 17, 566-568.

Schweiger, E. W., Leibowitz, S. G., Hyman, J. B., Foster, W. E., & Downing, M. C. 2002. Synoptic assessment of wetland function: a planning tool for protection of wetland species biodiversity. Biodiversity and Conservation 11, 379-406.

Sepp, K., Palang, H., Mander, l., & Kaasik, A. 1999. Prospects for nature and landscape protection in Estonia. Landscape and Urban Planning 46, 161-167.

Soulé, M. E. & Sanjayan, M. A. 1998. Conservation Targets: Do They Help? Science 279, 2060-2061.

Tear, T. H., Kareiva, P., Angermeier, P. L., Comer, P., Czech, B., Kautz, R., Landon, L., Mehlman, D., Murphy, K., Ruckelshaus, M., Scott, J. M., & Wilhere, G. 2005. How much is enough? The recurrent problem of setting measurable objectives in conservation. Bioscience 55, 835-849.

Tognelli, M. F., de Arellano, P. I. R., & Marquet, P. A. 2008. How well do the existing and proposed reserve networks represent vertebrate species in Chile? Diversity and Distributions 14, 148-158.

Traill, L. W., Bradshaw, C. J. A., & Brook, B. W. 2007. Minimum viable population size: A meta-analysis of 30 years of published estimates. Biological Conservation 139, 159-166.

Tucakov, M., Kalocsa, B., Tamas, A. E., Zuljevic, A., Erg, B., & Deme, T. 2006. The black stork Ciconia nigra between the Sio Channel and the Drava River in the central Danube floodplain: transboundary monitoring and protection plan. Biota (Race) 7.

Vanderkam, R. P. D., Wiersma, Y. F., & King, D. J. 2007. Heuristic algorithms vs. linear programs for designing efficient conservation reserve networks: Evaluation of solution optimality and processing time. Biological Conservation 137, 349-358.

Vazquez, L. B., Rodriguez, P., & Arita, H. T. 2008. Conservation planning in a subdivided world. Biodiversity and Conservation 17, 1367-1377.

Verboom, J., Foppen, R., Chardon, P., Opdam, P., & Luttikhuizen, P. 2001. Introducing the key patch approach for habitat networks with persistent populations: an example for marshland birds. Biological Conservation 100, 89-101.

Vuorisalo, T. & Laihonen, P. 2000. Biodiversity conservation in the north: history of habitat and species protection in Finland. Annales Zoologici Fennici 37, 281-297.

Wilhere, G. F. 2008. The How-Much-Is-Enough Myth. Conservation Biology 22, 514-517.

Williams, J., ReVelle, C., & Levin, S. 2005. Spatial attributes and reserve design models: A review. Environmental Modeling and Assessment 10, 163-181.

Williams, L., Zazanashvili, N., Sanadiradze, G., & (eds.) 2005. *Ecoregional conservation plan for the Caucasus* WWF; Tbilisi.

Williams, P. H. & Araujo, M. B. 2002. Apples, oranges, and probabilities: Integrating multiple factors into biodiversity conservation with consistency. Environmental Modeling & Assessment 7, 139-151.

Zhou, N. Q., Wang, Y., & Li, C. X. 2007. *The carbon cycle in wetlands and its relationship to global change* Taylor & Francis, London.

Appendix

Table 1: Wetland species of European conservation concern

	Scientific name	Vernacular name
Amphibians	*Alytes muletensis*	Mallorcan midwife toad
	Bombina bombina	Fire-bellied toad
	Bombina variegata	Yellow-bellied toad
	Chioglossa lusitanica	Golden-striped salamander
	Discoglossus galganoi[1]	Iberian painted frog
	Discoglossus montalentii	Corsican painted frog
	Discoglossus sardus	Tyrrhenian painted frog
	Pelobates fuscus insubricus	Common spadefoot
	Rana latastei	Italian agile frog
	Salamandrina terdigitata	Spectacled salamander
	Triturus carnifex	Italian crested newt
	Triturus cristatus	Great crested newt
	Triturus dobrogicus	Danube crested newt
	Triturus karelini	Southern crested newt
	Triturus montandoni	Carpathian newt
	Triturus vulgaris ampelensis	Smooth newt
Reptiles	*Elaphe quatuorlineata*	Four-lined snake
	Emys orbicularis	European pond tortoise
	Mauremys caspica	Stripe necked terrapin
	Mauremys leprosa	Spanish terrapin
Birds	*Acrocephalus paludicola*	Aquatic warbler
	Alcedo atthis	Kingfisher
	Anser erythropus	Lesser white-fronted goose
	Aquila chrysaetos	Golden eagle
	Aquila clanga	Spotted eagle
	Ardea purpurea purpurea	Purple heron
	Ardeola ralloides	Squacco heron
	Asio flammeus	Short-eared owl
	Aythya nyroca	Ferruginous duck
	Botaurus stellaris stellaris	Bittern
	Chlidonias hybridus	Whiskered tern
	Chlidonias niger	Black tern
	Ciconia ciconia	White stork
	Ciconia nigra	Black stork
	Crex crex	Corncrake
	Fulica cristata	Crested coot
	Gavia arctica	Black-throated diver
	Gelochelidon nilotica	Gull-billed tern
	Glareola pratincola	Collared pratincole
	Grus grus	Crane
	Haliaeetus albicilla	White-tailed eagle
	Hoplopterus spinosus	Spur-winged plover
	Ixobrychus minutus minutus	Little bittern
	Marmaronetta angustirostris	Marbled teal
	Milvus migrans	Black kite
	Nycticorax nycticorax	Night heron
	Oxyura leucocephala	White-headed duck
	Pandion haliaetus	Osprey
	Pelecanus crispus	Dalmatian pelican

	Pelecanus onocrotalus	White pelican
	Phalacrocorax pygmaeus	Pygmy cormorant
	Philomachus pugnax	Ruff
	Platalea leucorodia	Spoonbill
	Plegadis falcinellus	Glossy ibis
	Porphyrio porphyrio	Purple gallinule
	Porzana parva parva	Little crake
	Porzana porzana	Spotted crake
	Porzana pusilla	Baillon´s crake
	Sterna albifrons	Little tern
	Tadorna ferruginea	Ruddy shelduck
	Tringa glareola	Wood sandpiper
Mammals	*Castor fiber*[2]	Eurasian beaver
	Galemys pyrenaicus	Pyrenean desman
	Lutra lutra	European otter
	Microtus cabrerae	Cabrera's vole
	Microtus oeconomus arenicola	Dutch root vole
	Microtus oeconomus mehelyi	Pannonian root vole
	Mustela lutreola	European mink
	Myotis capaccinii	Long-fingered bat
	Myotis dasycneme	Pond bat

[1] including *Discoglossus jeanneae*
[2] except the Estonian, Latvian, Lithuanian, Finnish and Swedish populations (according to 92/43/EEC)

Table 2: Minimum viable population sizes and density data

Scientific name	Minimum viable population size[1] [reproductive units]	Maximum density[2,3] [reproductive units/hectare]
Alytes muletensis	200	20
Bombina bombina	200	20
Bombina variegata	200	20
Chioglossa lusitanica	200	10
Discoglossus galganoi	200	10
Discoglossus montalentii	200	10
Discoglossus sardus	200	10
Pelobates fuscus insubricus	200	10
Rana latastei	200	20
Salamandrina terdigitata	200	10
Triturus carnifex	200	10
Triturus cristatus	200	10
Triturus dobrogicus	200	10
Triturus karelini	200	10
Triturus montandoni	200	10
Triturus vulgaris ampelensis	200	20
Elaphe quatuorlineata	120	2
Emys orbicularis	120	15
Mauremys caspica	120	9
Mauremys leprosa	120	9
Acrocephalus paludicola	200	1.09
Alcedo atthis	200	0.15
Anser erythropus	200	0.127
Aquila chrysaetos	120	0.0002
Aquila clanga	120	0.000055
Ardea purpurea purpurea	120	0.199478
Ardeola ralloides	200	0.199999
Asio flammeus	200	0.1
Aythya nyroca	200	1
Botaurus stellaris stellaris	200	0.5
Chlidonias hybridus	200	0.199997
Chlidonias niger	200	0.199987
Ciconia ciconia	120	0.001415
Ciconia nigra	120	0.00018
Crex crex	200	0.198751
Fulica cristata	200	10
Gavia arctica	120	0.006
Gelochelidon nilotica	200	0.199999
Glareola pratincola	200	8
Grus grus	120	0.00043
Haliaeetus albicilla	120	0.01273
Hoplopterus spinosus	200	0.3846
Ixobrychus minutus minutus	200	1.97
Marmaronetta angustirostris	200	0.199997
Milvus migrans	120	1.2733
Nycticorax nycticorax	200	0.199938
Oxyura leucocephala	200	1.5
Pandion haliaetus	120	0.0004
Pelecanus crispus	120	0.199997
Pelecanus onocrotalus	120	0.199997

Phalacrocorax pygmaeus	200	0.199501
Philomachus pugnax	200	1
Platalea leucorodia	120	0.199996
Plegadis falcinellus	200	0.199997
Porphyrio porphyrio	200	3.3
Porzana parva parva	200	5
Porzana porzana	200	0.333
Porzana pusilla	200	3.5368
Sterna albifrons	200	0.199987
Tadorna ferruginea	120	10
Tringa glareola	200	0.12
Castor fiber	120	0.002
Galemys pyrenaicus	200	13.89
Lutra lutra	120	0.00017
Microtus cabrerae	200	57.5
Microtus oeconomus arenicola	200	65
Microtus oeconomus mehelyi	200	65
Mustela lutreola	200	0.083
Myotis capaccinii	200	0.0042
Myotis dasycneme	200	0.0042

[1] adapted from Verboom et al. 2001

[2] densities colonial birds: distinction in nesting and foraging area; foraging area is set to 5 ha per reproductive unit (0,2 reproductive units per hectare)

[3] densities amphibians: 10 reproductive units per hectare for solitary species; 20 reproductive units per hectare for gregarious species

Table 3: Required and optional habitat types (x: required, /: optional)

Scientific name	Mire	Wet forest	Wet grassland	Water course	Water body	Open water[1]
Alytes muletensis				x		
Bombina bombina			x		x	
Bombina variegata		/	/		x	
Chioglossa lusitanica				x		
Discoglossus galganoi					x	
Discoglossus montalentii				x		
Discoglossus sardus					x	
Pelobates fuscus insubricus					x	
Rana latastei		x			x	
Salamandrina terdigitata				x		
Triturus carnifex		/	/		x	
Triturus cristatus		/	/		x	
Triturus dobrogicus			/		x	
Triturus karelini					x	
Triturus montandoni		x	/		x	
Triturus vulgaris ampelensis		/	/		x	
Elaphe quatuorlineata			/			
Emys orbicularis					x	
Mauremys caspica						x
Mauremys leprosa						x
Acrocephalus paludicola			x			
Alcedo atthis						x
Anser erythropus		x				x
Aquila chrysaetos	/		/			
Aquila clanga	/	x	/	/	/	
Ardea purpurea purpurea			x			x
Ardeola ralloides			x		x	
Asio flammeus	/		/			
Aythya nyroca			x		x	
Botaurus stellaris stellaris			x			
Chlidonias hybridus			/		x	
Chlidonias niger			x		x	
Ciconia ciconia			x			x
Ciconia nigra		x				x
Crex crex	/		x	/		
Fulica cristata			x		x	
Gavia arctica					x	
Gelochelidon nilotica			x	x		
Glareola pratincola			x		x	
Grus grus	/	/	/		/	
Haliaeetus albicilla		x				x
Hoplopterus spinosus			x			x
Ixobrychus minutus minutus			x			x
Marmaronetta angustirostris			x		x	
Milvus migrans						x
Nycticorax nycticorax			x			x
Oxyura leucocephala					x	
Pandion haliaetus		/			x	
Pelecanus crispus			/		x	
Pelecanus onocrotalus			/		x	

Phalacrocorax pygmaeus		/	/		x	
Philomachus pugnax	/		/			
Platalea leucorodia		/	x		x	
Plegadis falcinellus		/	x		x	
Porphyrio porphyrio			x		x	
Porzana parva parva			x		/	
Porzana porzana	/		/			
Porzana pusilla			x			
Sterna albifrons				x	/	
Tadorna ferruginea					x	
Tringa glareola	x	/	/			
Castor fiber		x				x
Galemys pyrenaicus						x
Lutra lutra						x
Microtus cabrerae			x			
Microtus oeconomus arenicola	/		/	/	/	
Microtus oeconomus mehelyi	/		/	/	/	
Mustela lutreola			/	x	/	
Myotis capaccinii						x
Myotis dasycneme					x	

[1] open water: water course or water body

Table 4a: Allocation of species to countries (scenario: "coordinated conservation planning within countries")

EU 27 country[1,2]	Species
Bulgaria	*Triturus karelinii, Pelecanus crispus, Pelecanus onocrotalus, Phalacrocorax pygmeus, Plegadis falcinellus, Tadorna ferruginea*
Finland	*Asio flammeus, Philomachus pugnax*
France	*Bombina variegata, Discoglossus montalentii, Emys orbicularis, Alcedo atthis, Ixobrychus minutus, Milvus migrans, Nycticorax nycticorax, Mustela lutreola*
Germany	*Triturus cristatus, Myotis dasycneme*
Greece	*Mauremys caspica, Hoplopterus spinosus*
Hungary	*Platalea leucorodia, Microtus oeconomus mehelyi*
Italy	*Discoglossus sardus, Pelobates fuscus insubricus, Rana latastei, Salamandrina terdigitata, Triturus carnifex, Elaphe quatuorlineata, Myotis capaccinii*
Netherlands	*Microtus oeconomus arenicola*
Poland	*Bombina bombina, Triturus montandoni, Acrocephalus paludicola, Aythya nyroca, Botaurus stellari, Chlidonias niger, Ciconia ciconia, Ciconia nigra, Crex crex, Haliaeetus albicilla, Porzana parva, Porzana porzana, Sterna albifrons, Castor fiber*
Romania	*Triturus dobrogicus, Triturus vulgaris ampelensis, Aquila clanga, Ardeola ralloides, Chlidonias hybridus*
Spain	*Alytes muletensis, Chioglossa lusitanica, Discoglossus galganoi, Mauremys leprosa, Aquila chrysaetos, Ardea purpurea, Fulica cristata, Gelochelidon nilotica, Glareola pratincola, Marmaronetta angustirostris, Oxyra leucocephala, Porphyrio porphyrio, Porzana pusilla, Galemys pyrenaicus, Lutra lutra, Microtus cabrerae*
Sweden	*Anser erythropus, Gavia arctiva, Grus grus, Pandion haliaetus, Tringa glareola*

Table 4b: Allocation of species to biogeographical regions (scenario: "coordinated conservation planning within biogeographical regions")

Biogeographical region[3]	Species
alpine	*Triturus montandoni, Anser erythropus*
atlantic	*Chioglossa lusitanica, Microtus oeconomus arenicola, Mustela lutreola*
black sea	*Pelecanus onocrotalus*
boreal	*Asio flammeus, Gavia arctiva, Grus grus, Pandion haliaetus, Philomachus pugnax, Tringa glareola, Castor fiber*
continental	*Bombina bombina, Bombina variegata, Pelobates fuscus insubricus, Rana latastei, Triturus carnifex, Tritutus cristatus, Triturus karelinii, Triturus vulgaris ampelensis, Acrocephalus paludicola, Alcedo atthis, Aquila clanga, Ardeola ralloides, Aythya nyroca, Botaurus stellaris, Chlidonias niger, Ciconia ciconia, Ciconia nigra, Crex crex, Haliaeetus albicilla, Ixobrychus minutus, Milvus migrans, Pelecanus crispus, Phalacrocorax pygmeus,Porzana parva, Porzana porzana, Sterna albifrons, Lutra lutra, Myotis dasycneme*
mediterranean	*Alytes muletensis, Discoglossus galganoi, Discoglossus montalentii, Discoglossus sardus, Salamandrina terdigitata ,Elaphe quatuorlineata, Emys orbicularis, Mauremys caspica, Mauremys leprosa, Aquila chrysaetos, Ardea purpurea, Chlidonias hybridus, Fulica cristata, Gelochelidon nilotica, Glareola pratincola, Hoplopterus spinosus, Marmaronetta angustirostris, Nycticorax nycticorax, Oxyra leucocephala, Plegadis falcinellus, Porphyrio porphyrio, Porzana pusilla, Tadorna ferruginea, Galemys pyrenaicus, Microtus cabrerae, Myotis capaccinii*
pannonian	*Triturus dobrogicus, Platalea leucorodia, Microtus oeconomus mehelyi*

[1] Malta, Cyprus, and Macaronesia excluded due to lack of data

[2] Each species is allocated to the country in which most occupied planning units of the species are located; the twelve resulting countries encompass 79 % of the considered land area

[3] Each species is allocated to the biogeographical region in which most occupied planning units of the species are located; the seven resulting regions encompass 99,3 % of the considered land area

Opportunity costs in conservation planning – of the case of European wetland species

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Abstract

Protected areas have often been designated ad hoc. Despite increasing conservation efforts, loss of biodiversity still accelerates. Considering land scarcity and demand for alternative uses, efficiency in conservation strongly depends on efficiency in land allocation. Systematic conservation planning can effectively prioritize conservation activities. Previous studies have minimized the costs for exogenously given conservation targets. However, these studies have assumed constant marginal costs of preservation. We extend this cost minimization approach by also considering an endogenous representation of marginal costs. The more land is allocated to nature reserves, the higher are opportunity costs, i.e. costs of forgone agricultural production. The increase in opportunity costs results from prices changes for agricultural commodities. We employ a deterministic, spatially explicit mathematical optimization model to allocate species habitats by minimizing opportunity costs for setting aside land for conservation purposes. Representing costs endogenously substantially enhances total costs for the empirical application to European wetland species.

1 Introduction

Reservation has often been done ad hoc, leading to non-optimal decisions on conservation areas (Gonzales et al., 2003;Margules and Pressey, 2000;Pressey, 1994). Protected areas are biased towards economically marginal landscapes which leads to severe underrepresentations of species, habitats, and ecosystems (Araujo et al., 2007;Pressey and Tully, 1994). Existing reserves are furthermore often too small to support viable populations of wide-ranging species (Boyd et al., 2008;Pullin, 2002). Thus, despite increasing conservation efforts, biodiversity loss still accelerates (Baillie et al., 2004;Myers et al., 2000).

Considering land scarcity and demand for alternative uses, efficiency in conservation strongly depends on efficiency in land allocation. Systematic conservation planning can effectively prioritize conservation activities (Margules and Pressey, 2000;Possingham et al., 2000). The set-covering problem detects how and where to protect as much biodiversity features as possible while minimizing the necessary resources for achieving the conservation objectives (Possingham et al., 2000;Williams et al., 2005).

In view of high competition for land especially in densely human-populated countries, the set-covering problem seems to be an area minimization problem first of all. Previous studies have minimized the number of reserve sites or their total area for given representation targets of biodiversity features (ReVelle et al., 2002;Saetersdal et al., 1993;Tognelli et al., 2008). However, minimum area requirement for reservation does not guarantee minimum costs for achieving the respective land. Actually, it may well happen that less land is more expensive to obtain than more land in different locations or priority setting to regions changes (Balmford et al., 2000;Naidoo et al., 2006;Polasky et al., 2001). Even more compelling are estimations that the cost per conservation site under cost minimization can be less than one-sixth of that under the site-minimizing solution (Ando et al., 1998). However, when appropriate data on land costs are not available, conservation planning studies still often use area as a substitute for costs (McDonnell et al., 2002).

When accounting for heterogeneity in land costs, previous studies have assumed marginal costs as being fixed and exogenous (Ando et al., 1998;Polasky et al., 2001;Stewart and Possingham, 2005). But, Naidoo et al. (2006) argue that setting aside land for conservation itself could change land costs. Armsworth et al. (2006) explicitly consider land market feedbacks with respect to conservation planning. Assuming constant marginal land costs neglects land market effects and thereby may lead to underestimations of real costs and thus non-optimal decisions on reservation.

Thus, the main research question we address in this study is: How relevant is the effect on conservation planning results of taking the dynamic nature of opportunity costs into account?

We employ a deterministic, spatially explicit mathematical optimization model, which allocates species habitats by minimizing total opportunity costs for setting aside land for conservation purposes. We apply integer programming techniques. To illustrate the effect of incorporating the dynamic nature of opportunity cost into conservation planning, we compare exogenous and endogenous representations of costs of a multiple-species conservation planning exercise. The analysis is done for European wetland species but is easily adaptable to other species, biodiversity features, or regions.

2 Methods

2.1 Conservation target

Effective biodiversity conservation requires simultaneous consideration of representation and persistence conditions (Margules and Pressey, 2000;Sarkar et al., 2006). In our model, each species has to reach exogenously assigned representation targets. These targets can differ across species. We assume the persistence criterion to be fulfilled when two conditions are met. First, a species has to be able to form at least one viable population each time it is represented. A population is considered viable when the allocated land area equals smallest the minimum critical area which is defined as follows:

minimum critical area = density * minimum viable population size for all species

This minimum critical area is a species-specific measure based on density data and assumptions on minimum viable population sizes. Density data can differ substantially depending on habitat quality (Foppen et al., 2000;Riley, 2002) or due to bias in sampling effort (Schwanghart et al., 2008). To account for that variability, we enable to solve the model for different density data. We do not explicitly portray competition between species and assume that they do not affect each other in terms of density.

The second condition for the persistence criterion refers to habitat type requirements. We assume that each species requires specific habitat types which are either necessary for the species' survival or optional habitats. The land area determined by the minimum critical area has to be allocated to the habitat types required by the relevant species.

2.2 Planning units

We use a spatially explicit model based on planning units that differ in shape and size. The maximum habitat area to be selected is determined for each planning unit. Available options are either to use the total planning unit area, a fraction of the planning unit, or real or estimated data on potential reserve areas per planning unit.

There are two possible states of each planning unit; it is either occupied by a species (1) or not (0). Only occupied planning units can be selected for a species. We assume that habitat suitability for a species is constant across all possible planning units.

Parts of planning units necessary to fulfill conservation targets are selected as priority area for conservation. If a species' minimum area requirement cannot be fulfilled within a single planning unit, we allow the model to choose further habitat area in adjacent planning units.

2.3 Land market feedbacks and marginal costs

When purchasing or renting large areas for conservation within a region, the supply and demand for land in regional land markets is affected. Regional dynamics in land markets do, in turn, determine the amount of conservation targets achievable and the costs of conservation effort in the future (Armsworth et al., 2006). The more land is allocated to nature reserves, the higher are opportunity costs, i.e. costs of forgone agricultural production. The increase in opportunity costs results from prices changes for agricultural commodities.

In economics, marginal cost is the change in total cost that arises when the quantity produced changes by one unit. Mathematically, the marginal cost function is expressed as the derivative of the total cost function with respect to quantity. Figure 1 displays typical shapes of constant and increasing marginal cost functions.

Figure 1 about here

To determine the slope of an increasing marginal cost function one needs to know how strong supply of land changes when land rents or prices change. We adopt the economic concept of price-elasticity of supply here which is defined as a numerical measure of the responsiveness of the quantity supplied of a product to a change in price of the product alone.

The formula used to calculate the coefficient of price elasticity of supply for a given product is:

$$E_s = \frac{\%\text{ change in quantity supplied}}{\%\text{ change in price}} = \frac{\Delta Q_s / Q_s}{\Delta P_s / P_s}$$

2.4 Mathematical optimization model

The formal framework used here follows and expands the set-covering problem. We use the following notation: $p = (1,\ldots,P)$ is the set of planning units; $t = (1,\ldots,T)$ is the set of habitat types; $q = (1,\ldots,Q)$ is the set of different habitat qualities; and $s = (1,\ldots,S)$ is the set of species. In addition we employ several mapping sets, which contain possible combinations between two or more individual indexes. In particular, $u(s,t)$ identifies the mapping between species and required or optional habitat types and $k(s,p,t)$ possible existence of species and habitats in each planning unit. The objective variable C represents the total opportunity costs. The variable Z_p represents the opportunity costs per planning unit p. The variable $Y_{p,t,q}$ determines the habitat area per planning unit p, habitat type t, and habitat quality q in hectares. $X_{s,p}$ is a binary variable with $X_{s,p} = 1$ indicating species s is chosen in planning unit p, and $X_{s,p} = 0$ otherwise. r_p represents the yearly land rent per hectare per planning unit p. $a_{p,t}$ is the maximum available area to be selected per planning unit p and habitat type t. $d_{s,q}$ represents species- and habitat quality-specific density data. m_s is a species-specific proxy for minimum viable population size. The parameter h_s determines which habitat types t are required by species s. t_s is the representation target per species s. If a species occurs less than the representation target, v_s allows a deviation from the target.

I Cost minimization with exogenous representation of costs

Minimize $C = \sum_p Z_p$ [1]

subject to:

$$Z_p \geq r_p \cdot \sum_{h,q} Y_{p,h,q}$$ for all p, [2]

$$\sum_{q} Y_{p,t,q} \leq a_{p,t} \qquad \text{for all p,t,} \qquad [3]$$

$$\sum_{t,q} d_{s,q} \cdot Y_{p,t,q} \geq m_s \cdot X_{s,p} \qquad \text{for all p,s,} \qquad [4]$$

$$\sum_{q} Y_{c,t,q} \geq h_{t,s} \cdot X_{s,p} \qquad \text{for all p,t,s,} \qquad [5]$$

$$\sum_{p} X_{s,p} \geq t_s - v_s \qquad \text{for all s,} \qquad [6]$$

$$\sum_{t,q} d_{s,q} \cdot Y_{p,t,q} \Big|_{k(s,p,t) \wedge u(s,t)} \geq m_s \cdot X_{s,p} \qquad \text{for all s,p,} \qquad [7]$$

$$\sum_{p,t,q} d_{s,q} \cdot Y_{p,t,q} \Big|_{k(s,p,t)} \geq t_s \cdot m_s \qquad \text{for all s.} \qquad [8]$$

The objective function [1] minimizes the total opportunity costs across all planning units. Constraint [2] defines the total costs per planning unit as product of habitat area and land rent. Constraint [3] limits habitat areas in each planning unit to given endowments. Constraint [4] ensures that the habitat area in a planning unit that is selected for the conservation of a particular species, is large enough to support a viable population of that species. Constraint [5] forces the existence of required habitat types for all species which are chosen in a particular planning unit. Constraint [6] implements the representation targets for all species. This constraint allows a deviation from the target if the number of occurrences of a species is less than the representation target. Constraint [7] portrays minimum area requirements for all protected species in all planning units. The summation over habitat types depicts the choice between possible habitat alternatives. Constraint [8] ensures that the total population size equals at least the representation target times the minimum viable population size. This constraint is especially relevant for cases, where the representation target is higher than the number of available planning units for conservation. For example, a representation target of ten viable populations with historical occurrences in only nine planning units would under [8] require at least one planning unit to establish enough habitat for two viable populations.

II Cost minimization with endogenous representation of costs

To calculate the costs endogenously, we alter the model formulation.

r^0_p now represents the initial land rent of one hectare land per planning unit. a^0_p is the initially available habitat area per planning unit. Land rents rise according to function $f(Y_{p,t,q})$. We assume a linear marginal cost function $f(Y_{p,t,q})$ with slope *b*.

$$f(Y_{p,t,q}) = r_p^0 + b * \sum_{t,q} Y_{p,t,q}$$

To determine *b* we need to introduce price-elasticity of supply ε. Elasticity ε defines percentage change of supply in relation to percentage change of land rent.

$$\varepsilon_{Y_{p,t,q},r_p} = \left| \frac{\partial \sum_{t,q} Y_{p,t,q}}{\partial r_p} \cdot \frac{r_p}{\sum_{t,q} a^0_{p,t,q}} \right| = \left| \frac{1}{b} \cdot \frac{r_p}{\sum_{t,q} a^0_{p,t,q}} \right|$$

The linear marginal cost function $f(Y_{p,t,q})$ now is represented through:

$$f(Y_{p,t,q}) = r_p^0 + \varepsilon' \cdot \frac{r_p}{\sum_t a^0_{p,t}} \cdot \sum_{t,q} Y_{p,t,q}$$

The corresponding total cost function $F(Y_{p,t,q})$ is:

$$F(Y_{p,t,q}) = r_p^0 \cdot \sum_{t,q} Y_{p,t,q} + 0{,}5 \cdot \varepsilon' \cdot \frac{r_p^0}{\sum_t a^0_{p,t}} \cdot \sum_{t,q} Y^2_{p,t,q}$$

In the model formulation, constraint [2] is to be replaced with [2a]:

$$Z_p \geq r_p^0 \cdot \sum_{t,q} Y_{p,t,q} + 0{,}5 \cdot \varepsilon' \cdot \frac{r_p^0}{\sum_t a^0_{p,t}} \cdot \sum_{t,q} Y^2_{p,t,q} \qquad \text{for all p.} \qquad [2a]$$

The problem is solved with mixed integer programming (MIP) using the general algebraic modelling system (GAMS) software version 22.9.

3 Application to European wetland biodiversity

3.1 Ecological and spatial data

Due to their relevance for conservation and related environmental objectives, we apply our model to freshwater wetland habitats. Freshwater wetland dependent species serve as surrogates for biodiversity. In this study, we consider the 69 tetrapod wetland species listed in the Appendixes of the birds and the habitats directive (79/409/EEC; 92/43/EEC) which include 15 amphibian, 4 reptile, 41 breeding bird, and 9 mammal species. Recorded occurrences from species' atlases (Gasc et al., 1997;Hagemeijer and Blair, 1997;Mitchell-Jones et al., 1999) identify their potential distribution in Europe.

Density data for the species were compiled through extensive literature review; we use the maximum observed density. The proxies for minimum viable population sizes are based on Verboom et al. (2001). We adapt their proposed standards for minimum population sizes depending on species' body sizes and life expectancy. One viable population in our model represents 120 reproductive units (pairs/territories/families; depending on species group) of long lived/large vertebrates and 200 reproductive units of middle-long lived/medium sized and short-lived/small vertebrates respectively.

Data on habitat type requirements result from literature review. We include five broad wetland habitat types in our dataset, namely mire, wet forest, wet grassland, water course, and water body. A further type "open water" is applied to species that either require water courses or water bodies.

Geographically estimated wetland data from Schleupner (2007) provide information on the available areas of the included habitat types. To enable the most area-demanding species to fulfill their area requirements, they are allowed to additionally inhabit unsealed land area ("other habitat"). See supplementary material for the included ecological data for the 69 wetland species.

The dataset comprises the European Union with 23 out of 27 member states (see Figure 2). Cyprus, Malta, the new member states Romania and Bulgaria, and Macaronesia were excluded from the analysis due to data deficiencies.

Figure 2 about here

The planning units reflect the resolution of the available occurrence data of the species. The atlases use the Universal Transverse Mercator (UTM) projection with grid squares of about 50 km edge length. We considered the terrestrial parts of all 1996 grid cells belonging to the selected European countries as planning units.

3.2 Economic data

European land statistics provided country-specific data on agricultural land rents (see Table 1). Though we would prefer values of undeveloped land, values of agricultural land are reasonable proxies as they reflect market conditions.

We derived the numerical measure of price-elasticity of supply from the economic land-use model EUFASOM (European Forest and Agricultural Sector Optimization Model) (Schneider et al., 2008). We use a value of 0.29 for elasticity ε across all included countries, which represents a relatively inelastic price-elasticity of supply.

3.3 Empirical Results

Figure 3 shows yearly land costs for conservation targets from 1 to 25 for 69 wetland species. The model with exogenous cost representation continously underestimates total costs when compared to the model version that includes land market feedbacks. Exogenously calculated costs are about 2,0 to 27,9 Percent (mean: 19,2 Percent) less than endogenously determined costs.

Figure 3 about here

Figure 4 shows land costs only from the exogenous cost model version. We compare the actual model-based costs with the hypothetical costs that arise from the same set of planning units when considering the costs endogenously. To obtain these hypothetical costs we treated the results from the exogenous cost model as given and recalculated - without optimization - the costs endogenously. These costs are about three to five times higher than the endogenously calculated costs shown in Figure 3. Also, it may well happen that costs for a higher target are lower that for a lower target.

Figure 4 about here

The total area required for achieving the conservation targets as well as the shares of the different habitat types do not differ significantly between the two cost representations (see Figure 5 and Figure 6). What does differ is the regional land allocation, in our case to the European Union member states (see Figure 7). Strong concentration of habitat area in the cheapest possible regions are hampered by including land market feedbacks into reserve site selection.

Figure 5, 6, and 7 about here

4 Discussion

Nature conservation is often costly and resources available are scarce. Applying economic concepts and models to conservation decision-making is therefore indispensable (Naidoo et al., 2006;Shogren et al., 1999;Watzold et al., 2006). Our approach shows that ignoring land market feedbacks can lead to cost-ineffective solutions in reserve selection procedures. Total land costs are severely underestimated by at the mean almost 20 Percent in the case of European wetland species.

To abate this problem, one could think of adding a – more or less arbitrary – markup on exogenously calculated total costs; derived from studies like the one we show here. Note that such a proceeding would not lead to optimal decision-making. As displayed in Figure 3, recalculating exogenously determined costs makes clear that the set of planning units chosen does not represent optimally located priority areas for reservation. Sticking to those sites would make reservation more costly than necessary.

As Cullen et al. (2005) pointed out, can failure to apply economic tools to decision making in conservation problems lead to errors in project selection, wasted use of scarce resources, and lower levels of conservation than possible to achieve from given resources. Newburn et al.'s (2005) review on reserve design approaches concludes that land costs are often inadequately addressed. The case of neglecting the dynamic nature of land opportunity costs is an illustrative example for possible waste of funds.

Polasky et al. (2008) stated that assuming constant land prices is reasonable when agricultural and forestry commodities are sold on a market in which the local production of the area of conservation interest does only represent a small fraction of total supply. Armsworth et al. (2006), however, remarks that land market feedbacks can undermine conservation efforts even at local scales. Thus, only when designing reserve selection problems for small regions with marginal impact on the market of agricultural and forestry goods, we should carefully take ignoring land market feedbacks into consideration.

We made two important simplifications in our analysis. First, we assumed a linear marginal cost function. We did so here in order to limit computation time. Second, we set opportunity costs equal to land rents. Reality in conservation planning is much more complex as not only potential agricultural land may be of conservation interest. Furthermore, there is a range of additional costs of considerable amount of importance in reservation, e.g. implementation and management cost (Naidoo et al., 2006). For reasons of clarity and lack of data, we consider here only the land opportunity costs. They should be seen as a proxy for setting aside land for conservation.

We analysed opportunity costs only with regard to renting or purchasing land for reservation. Note that opportunity costs are also relevant in other conservation issues not included in our study. In some cases management practices of landowners change and are compensated for. For example, Barlow et al. (2007) estimated the foregone forestry potentials when managing forest for maintaining habitat of several endangered species. Rondinini and Boitani (2007) estimated the costs of dealing with conflicts related to large carnivores.

5 Implications for conservation planning – When is including a dynamic representation of costs beneficial?

We can achieve much higher conservation objectives for the same amount of money spent when implementing opportunity costs into conservation planning. However, when considering land costs, we have to realize that they are complex and behave dynamic due to land market feedbacks.

Implementing opportunity costs endogenously in reserve selection models requires reliable data on price-elasticity of land. Additionally, the approach is easily applicable only when using exact algorithms instead of iterative heuristics to solve reserve selection problems.

Considering the dynamic nature of costs seems particular important in cases where (i) land rents or prices are comparably high, (ii) high competition for land occurs, or (iii) a great fraction of land is to be reserved within a region. Ignoring land market feedbacks in such cases may lead to severe underestimations of real costs as well as to non-optimal decisions on reservation.

Nevertheless, in other circumstances does accounting for costs endogenously not necessarily enhance optimality or accuracy in conservation planning. In particular cases, e.g. when only small regional reserve sites are to be established or in regions where constant marginal costs have been observed, conservation planning decisions will probably do not have a relevant effect on land costs.

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Reference List

Ando, A., Camm,J., Polasky,S., Solow,A., 1998. Species distributions, land values, and efficient conservation. Science 279, 2126.

Araujo, M.B., Lobo,J.M., Moreno,J.C., 2007. The Effectiveness of Iberian Protected Areas in Conserving Terrestrial Biodiversity. Conservation Biology 21, 1423-1432.

Armsworth, P.R., Daily,G.C., Kareiva,P., Sanchirico,J.N., 2006. Land market feedbacks can undermine biodiversity conservation. Proceedings of the National Academy of Sciences 103, 5403-5408.

Baillie,J.E.M., Hilton-Taylor,C., and Stuart,S.N., 2004. IUCN Red List of Threatened Species: A Global Species Assessment. IUCN, Gland (Switzerland).

Balmford, A., Gaston,K.J., Rodrigues,A.S.L., James,A., 2000. Integrating costs of conservation into international priority setting. Conservation Biology 14, 597-605.

Barlow, R., Grado,S., Miller,D., Grebner,D., 2007. Opportunity costs of managing for wildlife habitat in the North Central Hills region of Mississippi. Southern Journal of Applied Forestry 31, 39-46.

Boyd, C., Brooks,T.M., Butchart,S.H.M., Edgar,G.J., da Fonseca,G.A.B., Hawkins,F., Hoffmann,M., Sechrest,W., Stuart,S.N., van Dijk,P.P., 2008. Spatial scale and the conservation of threatened species. Conservation Letters 1, 37-43.

Cullen, R., Hughey,K.F.D., Fairburn,G., Moran,E., 2005. Economic analyses to aid nature conservation decision making. Oryx 39, 327-334.

Foppen, R.P.B., Chardon,J.P., Liefveld,W., 2000. Understanding the role of sink patches in source-sink metapopulations: Reed Warbler in an agricultural landscape. Conservation Biology 14, 1881-1892.

Gasc,J.P., Cabela,A., Crnobrnja-Isailovic,J., Dolmen,D., Grossenbacher,K., Haffner,P., Lescure,J., Martens,H., Martínez Rica,J.P., Maurin,H., Oliveira,M.E., Sofiandou,T.S., Veith,M., and Zuiderwijk,A., 1997. Atlas of amphibians and reptiles in Europe. Societas Europaea Herpetologica, Muséum National d'Histoire Naturelle & Service du Petrimone Naturel, Paris, -496 pp.

Gonzales, E.K., Arcese,P., Schulz,R., Bunnell,F.L., 2003. Strategic reserve design in the central coast of British Columbia: integrating ecological and industrial goals. Canadian Journal of Forest Research-Revue Canadienne de Recherche Forestiere 33, 2129-2140.

Hagemeijer,W.J.M. and Blair,M.J., 1997. The EBCC Atlas of European Breeding Birds: Their Distribution and Abundance. T & A D Poyser, London.

Margules, C.R., Pressey,R.L., 2000. Systematic conservation planning. Nature 405, 243-253.

McDonnell, M.D., Possingham,H.P., Ball,I.R., Cousins,E.A., 2002. Mathematical methods for spatially cohesive reserve design. Environmental Modeling & Assessment 7, 107-114.

Mitchell-Jones,A.J., Amori,G., Bogdanowicz,W., Krystufek,B., Reijnders,P.J.H., Spitzenberger,F., Stubbe,M., Thissen,J.B.M., Vohralík,V., and Zima,J., 1999. The Atlas of European Mammals. Academic Press, London, 1-484 pp.

Myers, N., Mittermeier,R.A., Mittermeier,C.G., da Fonseca,G.A.B., Kent,J., 2000. Biodiversity hotspots for conservation priorities. Nature 403, 853-858.

Naidoo, R., Balmford,A., Ferraro,P.J., Polasky,S., Ricketts,T.H., Rouget,M., 2006. Integrating economic costs into conservation planning. Trends in Ecology & Evolution 21, 681-687.

Newburn, D., Reed,S., Berck,P., Merenlender,A., 2005. Economics and land-use change in prioritizing private land conservation. Conservation Biology 19, 1411-1420.

Polasky, S., Camm,J.D., Garber-Yonts,B., 2001. Selecting Biological Reserves Cost-Effectively: An Application to Terrestrial Vertebrate Conservation in Oregon. Land Economics 77, 68-78.

Polasky, S., Nelson,E., Camm,J., Csuti,B., Fackler,P., Lonsdorf,E., Montgomery,C., White,D., Arthur,J., Garber-Yonts,B., Haight,R., Kagan,J., Starfield,A., Tobalske,C., 2008. Where to put things? Spatial land management to sustain biodiversity and economic returns. Biological Conservation 141, 1505-1524.

Possingham,H., Ball,I., and Andelman,S., 2000. Mathematical methods for identifying representative reserve networks. In: S.Ferson and M.A.Burgman (Editors), Quantitative methods for conservation biology. Springer, New York, pp. 291-306.

Pressey, R.L., 1994. Ad Hoc Reservations - Forward Or Backward Steps in Developing Representative Reserve Systems. Conservation Biology 8, 662-668.

Pressey, R.L., Tully,S.L., 1994. The Cost of Ad Hoc Reservation - A Case-Study in Western New-South-Wales. Australian Journal of Ecology 19, 375-384.

Pullin,A.S., 2002. Conservation Biology. Cambridge University Press, Cambridge.

ReVelle, C.S., Williams,J.C., Boland,J.J., 2002. Counterpart models in facility location science and reserve selection science. Environmental Modeling & Assessment 7, 71-80.

Riley, J., 2002. Population sizes and the status of endemic and restricted-range bird species on Sangihe Island, Indonesia. Bird Conservation International 12, 53-78.

Rondinini, C., Boitani,L., 2007. Systematic Conservation Planning and the Cost of Tackling Conservation Conflicts with Large Carnivores in Italy. Conservation Biology 21, 1455-1462.

Saetersdal, M., Line,J.M., Birks,H.J.B., 1993. How to Maximize Biological Diversity in Nature-Reserve Selection - Vascular Plants and Breeding Birds in Deciduous Woodlands, Western Norway. Biological Conservation 66, 131-138.

Sarkar, S., Pressey,R.L., Faith,D.P., Margules,C.R., Fuller,T., Stoms,D.M., Moffett,A., Wilson,K.A., Williams,K.J., Williams,P.H., Andelman,S., 2006. Biodiversity conservation planning tools: Present status and challenges for the future. Annual Review of Environment and Resources 31, 123-159.

Schleupner, C. Estimation of Spatial Wetland Distribution Potentials in Europe. FNU-135. 2007. Hamburg, Hamburg University and Centre for Marine and Atmospheric Science.
Ref Type: Report

Schneider, U.A., Balkovic, J., de Cara, S., Franklin, O., Fritz, S., Havlik, P., Huck, I., Jantke, K., Kallio, M.A., Kraxner, F., Moiseyev, A., Obersteiner, M. The European Forest and Agriculture Optimisation Model - EUFASOM. 2008. Research Unit Sustainability and Global Change, Hamburg University. Working Papers.
Ref Type: Report

Schwanghart, W., Beck,J., Kuhn,N., 2008. Measuring population densities in a heterogeneous world. Global Ecology and Biogeography 17, 566-568.

Shogren, J.F., Tschirhart,J., Anderson,T., Ando,A.W., Beissinger,S.R., Brookshire,D., Brown,G.M., Coursey,D., Innes,R., Meyer,S.M., Polasky,S., 1999. Why economics matters for endangered species protection. Conservation Biology 13, 1257-1261.

Stewart, R., Possingham,H., 2005. Efficiency, costs and trade-offs in marine reserve system design. Environmental Modeling and Assessment 10, 203-213.

Tognelli, M.F., de Arellano,P.I.R., Marquet,P.A., 2008. How well do the existing and proposed reserve networks represent vertebrate species in Chile? Diversity and Distributions 14, 148-158.

Verboom, J., Foppen,R., Chardon,P., Opdam,P., Luttikhuizen,P., 2001. Introducing the key patch approach for habitat networks with persistent populations: an example for marshland birds. Biological Conservation 100, 89-101.

Watzold, F., Drechsler,M., Armstrong,C.W., Baumgartner,S., Grimm,V., Huth,A., Perrings,C., Possingham,H.P., Shogren,J.F., Skonhoft,A., Verboom-Vasiljev,J., Wissel,C., 2006. Ecological-economic modeling for biodiversity management: Potential, pitfalls, and prospects. Conservation Biology 20, 1034-1041.

Williams, J., ReVelle,C., Levin,S., 2005. Spatial attributes and reserve design models: A review. Environmental Modeling and Assessment 10, 163-181.

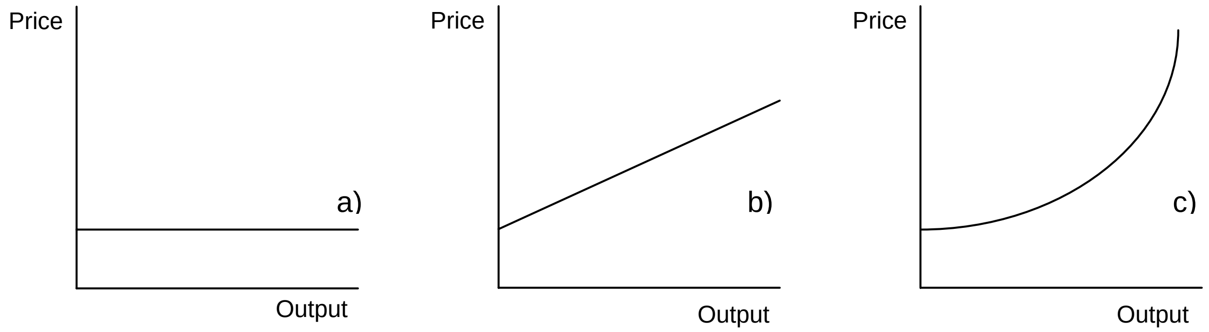

Figure 1: Marginal cost functions (a: constant; b: linearly increasing; c: quadratically increasing)

Figure 2: Spatial scope of empirical model application

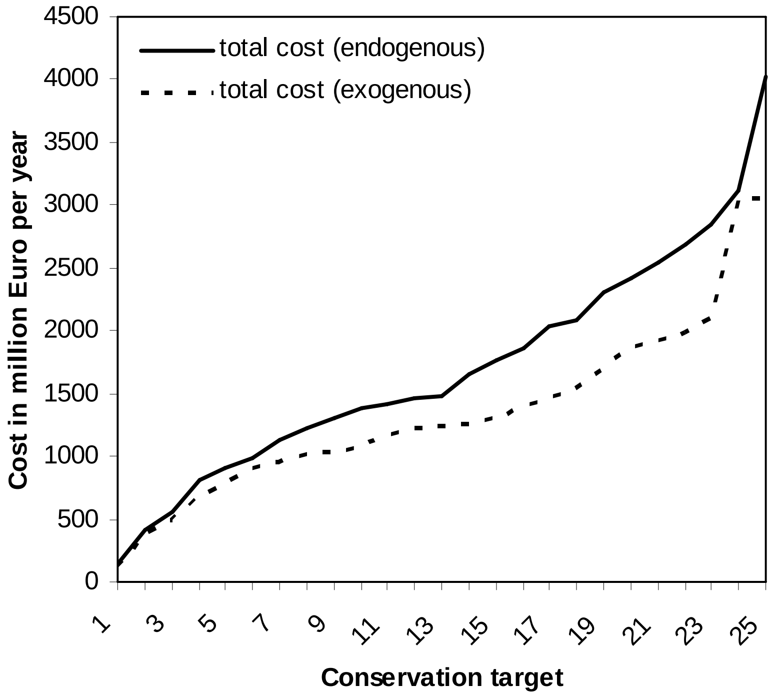

Figure 3: Total costs resulting from exogenous and endogenous representation of costs

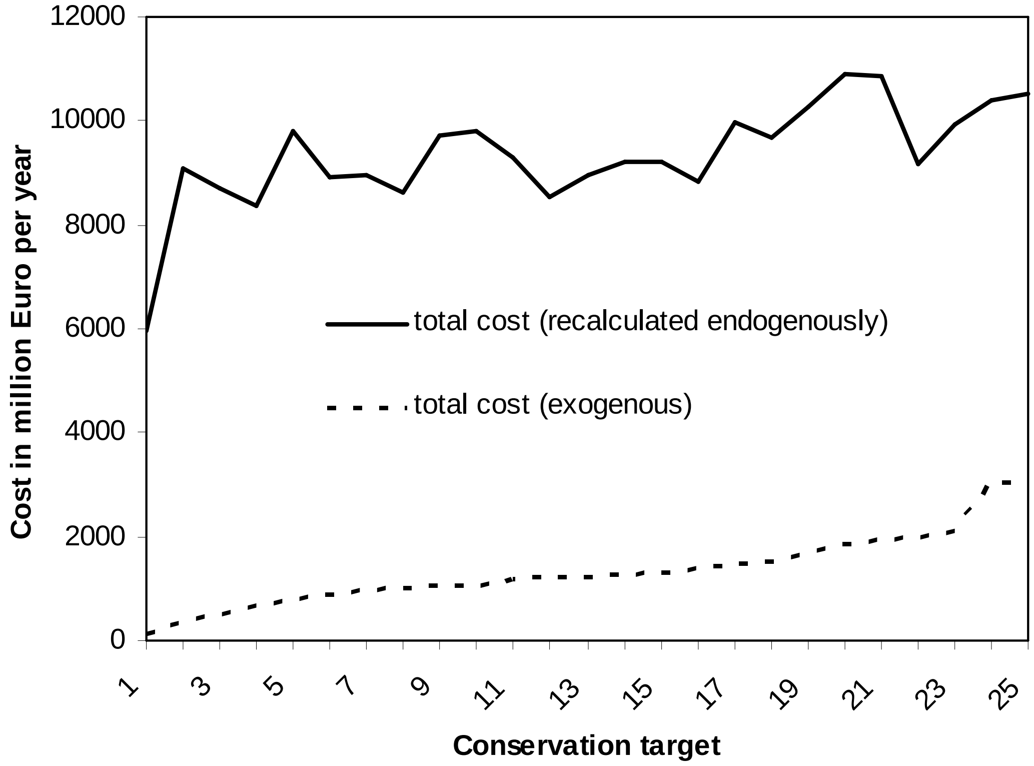

Figure 4: Total costs resulting from exogenous cost model version

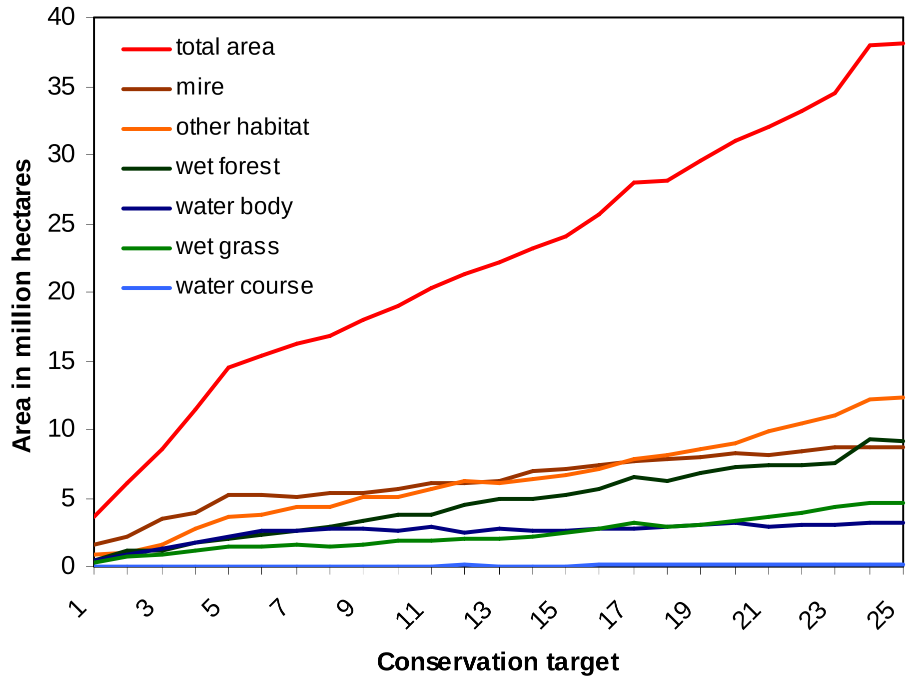

Figure 5: **Exogenous cost representation: allocation to wetland habitat types and total area requirement**

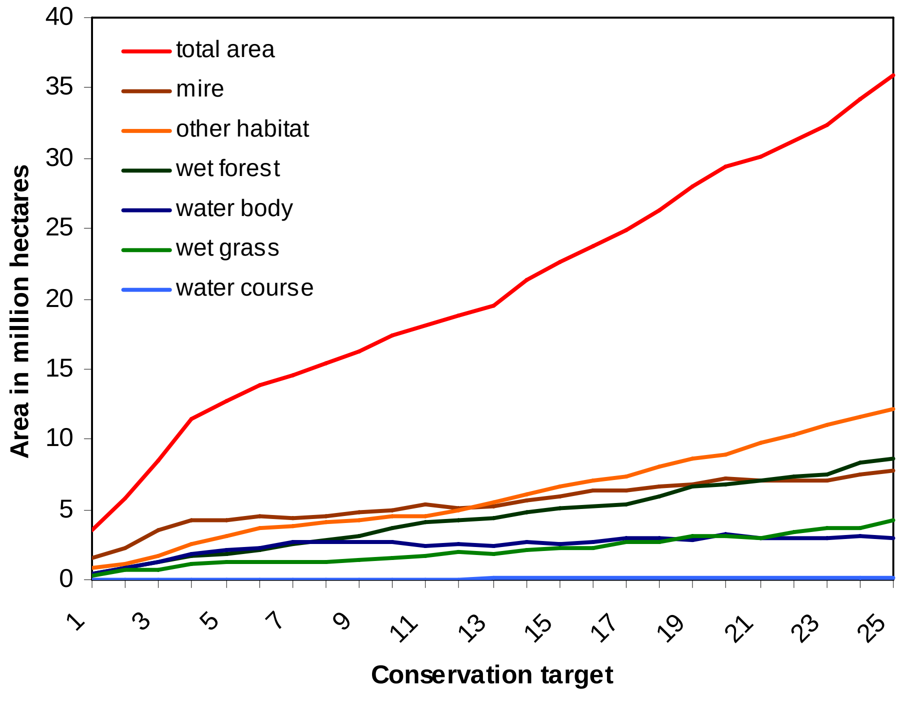

Figure 6: **Endogenous cost representation: allocation to wetland habitat types and total area requirement**

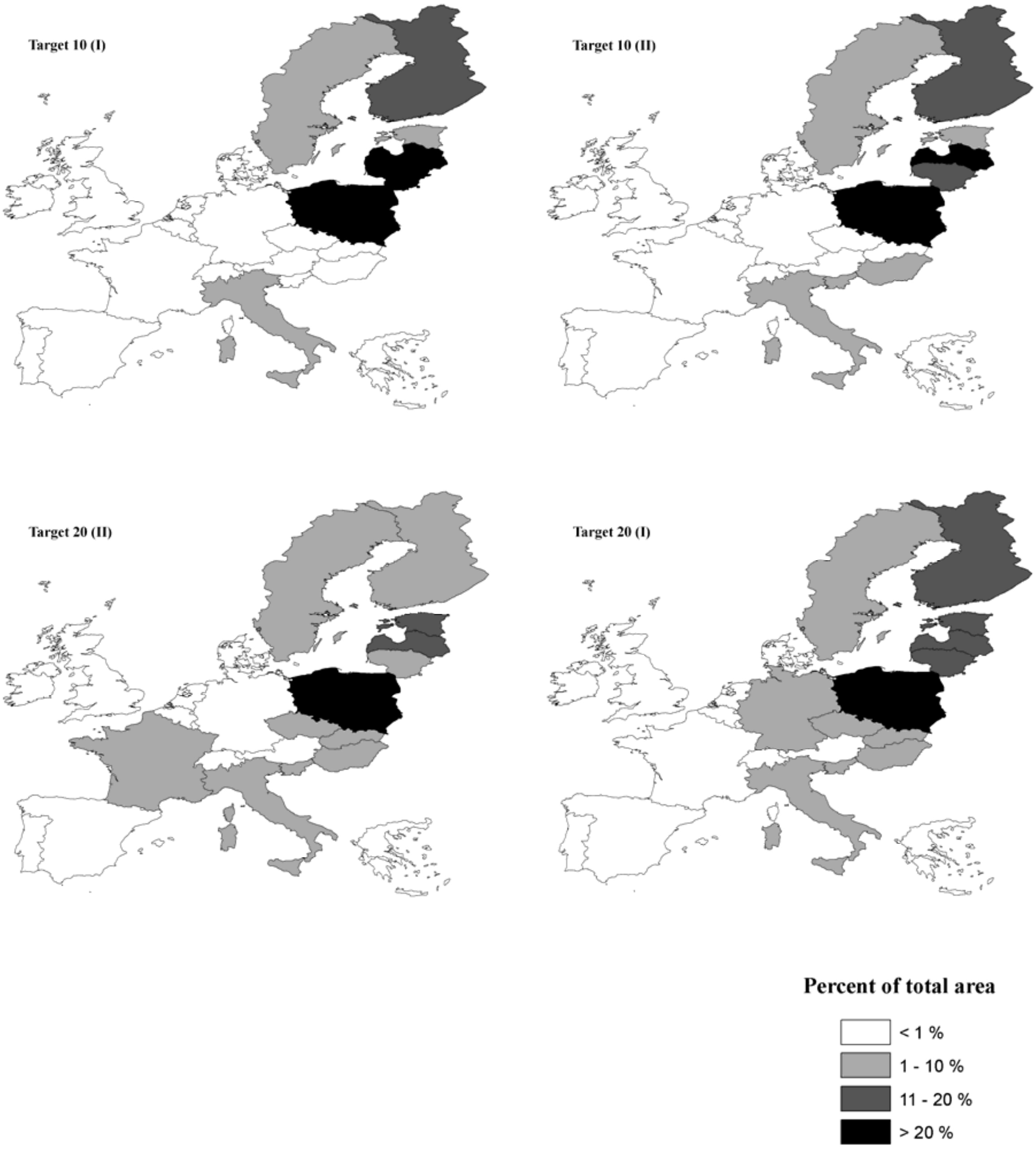

Figure 7: Regional allocation of total habitat area for exogenous (I) and endogenous (II) cost representations and conservation targets 10 and 20

Table 1: Agricultural land rents for EU25 countries

	Rent for agricultural land [€/ha*a][*]
Austria	244.53
Belgium	151.76
Czech Republic	23.17
Denmark	315.00
Estonia	15.76
Finland	152.08
France	109.35
Germany	156.32
Greece	402.98
Hungary	54.56
Ireland	212.76
Italy	248.42
Latvia	8.34
Lithuania	17.14
Luxembourg	150.38
Netherlands	396.01
Poland	68.08
Portugal	158.51
Slovakia	13.33
Slovenia	86.21
Spain	145.40
Sweden	98.12
United Kingdom	190.34

* data derived from Eurostat (averaged data from 1985 to 2006 for Austria, Belgium, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Lithuania, Luxembourg, Netherlands, Poland, Slovakia, Spain, Sweden, United Kingdom) and Farm Accountancy Data Network (FADN) (data from 2004 for Czech Republic, Estonia, Italy, Latvia, Portugal, Slovenia)

III.4. SBA CLIMATE by GEO-BENE Consortium Partners

Carbon Balance and Management

Commentary

Open Access

On fair, effective and efficient REDD mechanism design

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Abstract

The issues surrounding 'Reduced Emissions from Deforestation and Forest Degradation' (REDD) have become a major component of continuing negotiations under the United Nations Framework Convention on Climate Change (UNFCCC). This paper aims to address two key requirements of any potential REDD mechanism: first, the generation of measurable, reportable and verifiable (MRV) REDD credits; and secondly, the sustainable and efficient provision of emission reductions under a robust financing regime.

To ensure the supply of MRV credits, we advocate the establishment of an 'International Emission Reference Scenario Coordination Centre' (IERSCC). The IERSCC would act as a global clearing house for harmonized data to be used in implementing reference level methodologies. It would be tasked with the collection, reporting and subsequent processing of earth observation, deforestation- and degradation driver information in a globally consistent manner. The IERSCC would also assist, coordinate and supervise the computation of national reference scenarios according to rules negotiated under the UNFCCC. To overcome the threats of "market flooding" on the one hand and insufficient economic incentives for REDD on the other hand, we suggest an 'International Investment Reserve' (IIR) as REDD financing framework. In order to distribute the resources of the IIR we propose adopting an auctioning mechanism.

Auctioning not only reveals the true emission reduction costs, but might also allow for incentivizing the protection of biodiversity and socio-economic values. The introduced concepts will be vital to ensure robustness, environmental integrity and economic efficiency of the future REDD mechanism.

Introduction

The REDD process and the need for observations and decision support

Post-2012 emission mitigation strategies must lead to drastic emission reductions of greenhouse gases (GHGs) to prevent dangerous climate change. Accounting for some 18 percent of global anthropogenic GHG emissions in 2004 the reduction of emissions from deforestation and forest degradation (REDD) has become a prominent potential mitigation wedge. In effect, demonstration activities have flourished since the mandate given in the Bali Road Map of 2007 (UNFCCC Decision 2/CMP.13). Initiatives include the World Bank-hosted Forest Carbon Partnership Facility and Forest investment program, the UN-REDD program, Norway's International Climate and Forest Initiative, Australia's International Forest Carbon Initiative, and many other bilateral and private programs and projects. About 40 developing countries have already engaged in the process of designing REDD strategies. At times these various initiatives struggle to identify their synergies and avoid confusion regarding methodological and technical challenges. In particular, any system generating REDD credits is likely to operate within the scope of the principles stated in the Poznan Ministerial statement. These include, inter alia, the development of transparent, collaborative, balanced and inclusive international arrangements to support national REDD efforts. Decision makers also stressed that a reliable framework for measuring, reporting and verification (MRV) is crucial to the integrity and credibility of REDD. Key to the supply of MRV REDD credits is robust and consistent greenhouse gas (GHG) observation and monitoring systems combined with sound accounting methodologies and appropriate reference emission scenarios of deforestation and forest degradation (DD).

With respect to GHG accounting much progress has been achieved so far. It is generally believed that cost effective systems for estimating and monitoring deforestation and changes in carbon stocks can be designed and implemented using a combination of remote sensing assessments and ground based measurements [1]. However, guidance is needed to ensure comparable estimates when remote sensing is used, along with access to data, know-how and capacity building. Addressing forest degradation is especially difficult in this regard, but knowing the causes of degradation can help in designing meaningful stratified sampling approaches to measure it.

In short, the observation and monitoring challenges should not be viewed as a stumbling block for REDD policies to go ahead. However, efforts must be coordinated and streamlined through a robust international institutional arrangement, otherwise the environmental integrity and economic effectiveness of REDD is at risk.

Challenges in the design of reference levels and financial compensation

One of the most challenging aspects in designing a REDD mechanism is the estimation of reference levels (RL). They describe the amount of net/gross emissions and removals from a geographical area under a business-as-usual (BAU) development path. By describing the future emission pathway without any climate protection measures, reference scenarios are crucial to determine the success of emission reduction performances. Reference level can be solely based on historical emission trajectories or additionally take into account circumstances such as global deforestation rate, national forest area or deforestation drivers [2,3].

When it comes to setting RL there is less clarity on an agreeable methodology. This is related to different country circumstances and interests. On the one hand, countries with low past deforestation rates and potential high future deforestation will not agree to purely historically derived RL. To benefit from REDD and to prevent future deforestation those parties will rather propose to consider 'national circumstances' for RL setting, e.g. through a so-called 'Development Adjustment Factor'. On the other hand, many developing countries still lack sufficient technical and expert capacity to develop proper RL methodologies. Furthermore, if the process of developing and reporting such RL is not carefully designed, there is a risk of creating a so-called "lemons market" [4]. This occurs when the seller knows considerably more about the real quality of a product than the buyer, resulting in a reduced quality of supply of the respective product. In a REDD context, the "lemons" would materialize in the form of globally inconsistent and inflated RL adjustments, leading to non-additional emission reductions. Under a carbon market scheme this potentially results in an oversupply of cheap REDD credits. Because negative emission deviation from the RL would be matched by financial compensation, a credible method for the measurement of additional REDD units is absolutely essential for financial efficiency in the light of scarce resources dedicated to REDD [5] and avoiding the risk of artificial RL inflation [6].

Besides RL design the choice of the financial mechanism for a future REDD regime is intensely debated. Again, this is partly related to different developing country circumstances, but here the discussion is dominated by concerns about managing the potential oversupply for REDD credits under a market or lacking demand under a fund mechanism. Another major concern is the negative socio-economic and environmental effect of a sole carbon focus for REDD [7]. To overcome these risks the REDD mechanism might distribute compensation benefits (e.g. credits) not only based on the amount of emissions reduced, but also on the ecological and social value of the forests in question. Ideally, such form of REDD mechanism would aim to distribute credits to those REDD activities that provide the maximum total benefit from emission reduction, ecological and social values. However, since the financial consideration of co-benefits is currently only favoured by some parties its compulsory inclusion is likely to overburden the REDD policy negotiations. Additionally, financing and monitoring challenges previously mentioned also apply to co-benefit valuation.

This paper describes two linked proposals for the essential building blocks of REDD policy implementation. First, we propose an institutional REDD design aimed at generating globally consistent reference scenarios at the country level from which to derive MRV REDD credits. The second part of the paper describes a possible financial mechanism design for generating such REDD credits in an economically efficient manner, while incentivizing the valuation of forest co-benefits.

Discussion

Institutional support for transparent, fair and efficient reference level setting

Globally consistent DD emission reference scenarios at the national level are important for a large number of reasons. These include avoiding international leakage as well as ensuring transparency, fairness and efficiency. Fairness relates to the issue of relative distributional gain of financial resources made available. Compensation of future REDD actions against a historical RL will favour countries with a high historical emissions on a relative scale. This will increase the risk that future drivers of deforestation geographically shift to historical low deforestation countries and, thus, create asymmetric winner/looser profiles between REDD countries. In this sense low deforestation countries loose out two times under a purely historical baseline setting. First their supply potential for REDD is decreased and secondly their true baseline will be pushed up due to international leakage of REDD actions implemented in high deforestation countries. On a total market level "over-compensation" by countries with historically high deforestation due to a grandfathering rule will compromise both environmental integrity and cost effectiveness of REDD. Finally, such 'over-compensation' could lead to the supply of non-additional emission reductions and thus to an inflation of REDD credits [8].

Irrespective of the fact that reliable historical DD data do not exist for the Pan-tropical belt, the currently proposed methods to quantify RL on historical information will be insufficient without the consideration of national circumstances (drivers) and global data streamlining. Thus, we propose a system of establishing reliable and acceptable RLs based on a global forest information coordination body and RL algorithm implementation centre.

Data and quality requirements for reference level determination

The determination of the 'true' RL will not only shape global efficiency, but also be an important component for countries' planning REDD actions - regardless of how emissions reduction will be credited for. It is important to note that the 'true' BAU scenario does not have to be the same as the crediting RL [9]. The latter can be influenced by the 'Development Adjustment Factor' or eventually be the outcome of a negotiated "formula". Pure reliance on negotiation, however, potentially leads to political bargaining by strong actors. This could disadvantage less powerful developing countries in gaining financial access to REDD resources and threaten the environmental effectiveness of the REDD mechanism.

In the interest of fairness and efficiency, the final aim for RL determination will be that the 'true' BAU scenario and the crediting RL converge or in cases where the tropical countries are willing to take on responsibilities the crediting RL should be below the 'true" BAU baseline. To achieve this aim, it is essential to set up and implement harmonized and/or standardized rules and procedures for the collection, interpretation and consistent processing of various sources of forest data. These include earth observation data [10,11] as well as socio-economic data on the basic drivers and pressures for deforestation at national and international levels.

Data may include historical deforestation area measurements, estimates of the associated emissions and their uncertainties, current forest carbon stocks and carbon stock-change maps partitioned by the various carbon and nitrogen pools (e.g. soil, litter), and forest stand structure (e.g. species, age structure). These data can be sourced from a multitude of independent remote sensing instruments and their derived products such as http://www.geo-wiki.org[12], as well as from *in situ* data (primarily forest inventories) and possibly biophysical ecosystem models. What is important is that the data used by different countries should be publicly known, and models should be applied in a consistent manner by those countries, according to specific data and interoperability standards as well as to the respective greenhouse gas (GHG) accounting rules (e.g. Intergovernmental Panel on Climate Change and the Global Earth Observation System of Systems). The modelling tools themselves should also be standardized and certified.

Other types of input, necessary for countries to undertake consistent development of reference scenarios and planning of REDD policies, include activity data relating to the respective pressures and drivers of deforestation, as well as information on forest management planning, forestry supervision and inspection. Depending on the overall policy context of REDD implementation, such information should *inter alia* include not only forest ownership information, forest management plans with associated annual allowable cuts (AACs), and forest protection, but also information such as transportation infrastructure development, agricultural management data and food consumption projections. Such country-specific driver and governance information would have to be in line with scenarios of environmental and social change in a globally consistent manner. Consequently, emission pathways would also be generated in a consistent manner, addressing the issue of international leakage and possible GHG leakage to other sectors. An example would be land use related leakage in terms of N_2O emissions to the agricultural sector where REDD constraints land expansion, which must be compensated by intensified cultivation.

Both earth observation data and deforestation driver information could either be collected by national constituencies, according to a negotiated standard, or by international agencies in cooperation with national entities. In many countries, substantial capacity-building efforts would have to be undertaken to provide this information according to globally applicable standards, with sufficient quality and in a geographically explicit manner - if possible. Most importantly, earth observation data on past and the current state of the forest as well as DD driver information have to be collected, reported and subsequently processed in a globally consistent manner.

To achieve this globally consistent use of data and models, and thereby to arrive at fair and efficient REDD reference scenarios, a specific international institutional entity will be needed for the collection, interpretation and consistent processing of various sources of DD-related information at national and international levels. Figure 1 depicts a possible constellation of stakeholders and associated information flows.

The International Emission Reference Scenario Coordination Centre

To overcome the mentioned challenges we propose an International Emission Reference Scenario Coordination Centre (IERSCC) to assist countries in developing internationally recognized and accepted reference levels. It would act as a clearing house for harmonized data use in reference scenario modelling. The IERSCC, hosted by an independent forestry or land resources research institution of international status, will be tasked to develop global integrated assessment model(s) to deliver sector-specific national scenario information (e.g. trade flows, prices, socio-economic development information) to the respective REDD host countries. The latter would use this information as exogenous variables driving their national reference scenario model/algorithms. Ideally, these scenarios would, in turn, be determined by using geographically explicit, economic, bottom-up type models, whose methodologies could be validated by this or another international validation entity. Such international quality assurance would ensure internationally recognizable REDD reference scenarios of a national model(s) by providing confidence and information security to parties.

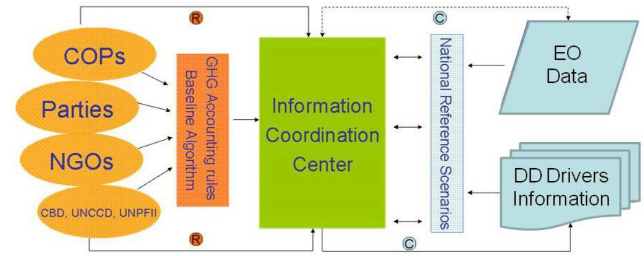

Figure 1

Institutional set up for determining harmonized reference emission scenarios for REDD. Under the proposed system national governments would collaborate with the International Emission Reference Scenario Coordination Centre (IERSCC) to build national capacity and to collect relevant deforestation driver and earth observation information. The IERSCC will assist countries in developing rules for establishing globally consistent national reference levels. Relevant entities such as the Conference of the Parties (COPs) to the UNFCCC, non-governmental organisations (NGOs) and other linked international treaties can support and guardrail this process. (EO = Earth Observation, DD = Deforestation and Degradation, R = Rules, C = Consistency).

Our proposed IERSCC would receive inputs from the respective UNFCCC bodies, in the form of agreed GHG accounting rules, as well as rules (possibly in algorithmic form and parameterization) of the computation procedures for globally consistent national reference scenarios. In this way, the IERSCC would function as an independent technical implementation body to the UNFCCC policy process by supporting and validating consistent collection of earth observation and other DD driver data, based on rules defined by the UNFCCC policy process. The body could also be tasked with developing and applying calibration routines of global top-down modelling with national bottom up modelling to generate consistency between the two.

National-level emission reference scenarios should, as far as possible, be based on geographically explicit data and analysis and allow for down-scaling of national scenarios to assist regional or project level activities. The latter would allow for tailored and targeted national and international REDD actions, since the quantity and the location of deforestation drivers would be better understood [6]. Furthermore, consistent RL setting will be essential for the economic efficiency of international REDD-related compensation mechanisms. Finally, the IERSCC could help in building capacity for REDD response strategies through additional scenario analysis and training of national experts on these issues. It will enable them to conduct their own analysis on national implementation strategies, but also to use part of the IERSCC's data to inform their negotiation strategies in a global context. Furthermore, the IERSCC model results could be used on the individual national level for many other land-use related planning purposes ranging from the analysis of agricultural development strategies all the way to infrastructure planning.

A REDD finance mechanism ensuring economic and environmental integrity

In the following section we introduce a novel financing approach for REDD, which is able to use the advantages of current proposals while minimizing their disadvantages.

Additionally we specify its functioning under an auctioning mechanism. We will show that this innovative approach optionally allows maximizing social and biodiversity co-benefits (in the following referred to as sustainability co-benefits) while ensuring economic efficiency.

Combining fund and market strength under an 'International Investment Reserve'

While the risks of direct carbon market inclusion of REDD credits are widely acknowledged, a fund approach might run short of the necessary financing to significantly reduce deforestation. Market-linked approaches like the TDERM [13] and Dual Markets approach [14] do not solve this dilemma, since they provide little incentives for Annex-1 governments to commit to ambitious REDD targets (and thus costs) besides their fossil fuel targets. In the light of current financial constraints on public spending due to the economic crisis and at the same time the overwhelming financing need for climate change adaptation and technology transfer, funds - no matter if originating from AAU earmarking, taxes or other sources- will be constrained.

An interesting alternative is provided by a so-called 'International Investment Reserve' (IIR) for REDD, based on the idea of a "Carbon Federal Reserve" (CFR) [15]. Under the IIR approach REDD providers (developing country governments and/or private carbon projects) would sell their, yet to be created, REDD units to the IIR at an agreed price. The REDD unit price should be below the carbon market credit value and possibly be discounted due to implementation risk and measurement uncertainties [16,17]. The IIR would be financed and managed by Annex-1 governments and possibly private investors. Contributions to the IIR could either be on a voluntary or mandatory basis. Participation for investments would be driven by the economic attractiveness of this scheme. Basically the IIR serves as investment bank for REDD, in which investors provide finance to buy REDD units. These units are then verified and banked, until market conditions are favorable to resell them as fungible MRV-based REDD credits to the carbon market. Given the long-term global emission reduction requirements many models project rising carbon credit prices [18]. This will allow considerable reselling profits - making the IIR an attractive investment option. To avoid market flooding the reselling can be made conditional, e.g. upon a maximum amount of credits per year and/or sufficient market demand signals to maintain competitive carbon prices. Similar to a stock market the IIR members would have an interest in reselling at high carbon market prices to increase the revenue compared to the buying price and thus to limit the risk of credit devaluation. In this way the banking and reselling conditions under the IIR can also contribute to a regulating effect in favor of price floors and caps in the carbon market. Additionally, to ensure environmental integrity reselling can also be made conditional on the overall allowable GHG concentration in the atmosphere, following a global emission budget approach [19].

The reserve would also provide a clear advantage for industrialized country governments for increasing their emission reduction commitments. Under the current situation governments would have to increase their national abatement targets in advance to avoid the risk of REDD credits flooding the carbon market. However, by doing so they take a high risk of belated or insufficient supply of REDD credits in the future. Given the unfavorable governance and capacity situation in many developing countries to successfully implement REDD [20] this risk is real. As a consequence these governments would have to substitute the lacking REDD supply with other emission abatement options which would increase the overall emission reduction costs considerably. Thus, from a strategic perspective governments would not choose higher abatement targets as dominant strategy for REDD, because the supply uncertainty would leave them in a situation of "first mover disadvantage". Under the IIR approach supply uncertainty would diminish, allowing governments to react to supply dynamics more flexible. Investment risks due to delivery failure would still be possible. However, they could be limited, if REDD unit payments from the IIR are divided into up-front financing and continued payments. In case fewer units are provided than initially offered, the difference is subtracted from the remaining payment obligations. Developing countries would also benefit from the IIR approach, since large financial flows could be generated in a timely manner. To increase their confidence in the mechanism, industrialized countries could commit a certain minimum financing amount for each auctioning period.

This is possible, since the IIR is compatible with nationally-obtained contributions in form of AAU earmarking and tax revenue finance for REDD as proposed by the European Commission [21]. At the same time governments or private investors can use other forms of investment. According to their financial share in the IIR each party (i.e. the respective government or private investor) obtains emission units from REDD suppliers. IIR members could either pool all units in a joint portfolio or differentiate them according to different criteria. For the first option they would be bought and collected in a common REDD unit portfolio. For the second option unit pools could be differentiated, e.g. by environmental and social co-benefit level. The latter option might require separate investment pools, if not all members agree on additional incentive payments for higher standards. These REDD units are then transferred into fungible, adjusted REDD credits to be sold at the international carbon market or used for increasing/meeting domestic abatement targets. The IIR approach would also have the advantage that risks of supply failure of REDD units as well as delivery failure of MRV standards could be minimized by pooling large REDD portfolios over time. By validating REDD units through the IERSCC before they are finally transferred the IIR can serve as quality catalyst for the carbon market or for national compliance.

Auctioning of MRV REDD units to account for sustainability co-benefits

Under a purely carbon-focused REDD approach, national-, regional- or project-level actions would be tailored to maximize emission reductions. However, aggressive implementation of REDD policies could run into conflict with basic food security issues [22], create social conflict and, under certain conditions, lead to further environmental degradation on a total landscape level [7,23]. Such conflicts can only be avoided if REDD policies are appropriately designed and implemented. In this respect, REDD policies can be treated in a similar manner as biofuels, as both are competing for land resources. Thus, it seems paramount that any action under the international REDD mechanism should simultaneously recognize the different ecological and social co-benefits that forests provide. Funds and hybrid-market approaches can better accompany such co-benefits than markets since they could differentiate rules and criteria for REDD co-benefits without being restricted to the carbon value or by credit buyer preferences. However, such approaches are prone to inefficiency in incentive distribution, because they will most likely operate based on fixed co-benefit premiums instead of individual opportunity costs.

The mechanism outlined below describes how the provision of essential co-benefits of REDD can be made attractive and how at the same time incentives can be allocated in a cost-efficient way using auctioning. For illustrative purposes we discuss here a 'sealed bid second price auction' mechanism, where potential buyers classically submit their price bid in sealed envelopes. The buyer with the highest price offered wins the bid, however, only has to pay the second highest bid price submitted. Since the winning bidder wins the difference between both prices it is a dominant strategy for the bidder to bid her true value in a 'sealed bid second price auction'. In a simple ' open ascending price auction' bidders would not bid their true value, as this would eliminate their profit margin.

In the REDD context a 'sealed bid second price auction' can work in a slightly different way. Here, we define the seller to be the supplier of REDD emission reduction units, whereas the buyer is the IIR. The IIR will initially distribute its available investment into a fixed amount of auctioning tranches. Emission reduction unit sellers will then submit sealed bid proposals with a minimum selling price per REDD unit and its targeted selling quantity to the REDD IIR. The IIR selects the best bidder, who then can sell its proposed quantity to the second-minimum selling price. If the tranche still contains money, the next best bidder can sell to the next lowest conditions. This continues until the finance is exhausted.

This auction can then be repeated in tranches of decreasing finance quantity, until the provided finance portfolio is exhausted or the targeted emission reduction quantity of the IIR is reached. The decreasing tranches provide incentives for REDD bidders to engage early in the auction to be able to sell all offered units and thus supply REDD credits at a price which better reflects their true cost of production.

Such an auctioning approach can ensure that a fixed quantitative REDD supply cap is achieved in a competitive setting. It also avoids excessive producer rents by minimizing a REDD arbitrage gap (this is the difference between the REDD costs and the potential revenue from Annex I emission reduction credit supply). Furthermore, auctioning allows for flexibility in targeting the allocation of supply by geographic or thematic areas [24,25].

Co-benefit dimensions cover thematic areas such as the retention of high conservation value forests and biodiversity and the provision of social benefits such as maintenance of employment or cultural services. What is needed for quantifying co-benefits prior to the auction is the identification (and verification) of the absolute or relative magnitude of these co-benefits. The measurement can be orientated on current, widely applied certification processes, or through other means of measuring and verifying sustainability co-benefits.

Using an auctioning approach there are two main options to account for ancillary benefits in the auctioning mechanism. Co-benefits could either be used as a qualifier criterion or as a criterion for the pricing. The qualifier criterion enables to participate in the financial compensation mechanism by achieving a certain quality standard. Besides the overall qualifier criterion to deliver measured, reported and verified (MRV) REDD units, additional social and environmental standards could be set for all REDD credit providers. If the REDD provider fails to achieve them, he would be excluded from the auction. Alternatively, where the aim is maximizing sustainability co-benefits of emission reductions under REDD, the competitive criterion can be the relative provision of sustainability co-benefits. They can be measured as the quantified and certified amount of ecosystem value points and social value points. It can be calculated according to pre-specified co-benefit assessment rules associated with the fungible REDD unit. Ideally, such a value system would be negotiated under the umbrella of a number of UN conventions and charters. However, since a political consensus on this issue is difficult to achieve, the determination of the assessment rules could alternatively be restricted by the parties involved in the financing of such co-benefits. The relative co-benefit performance would then be translated into a co-benefit factor. Such factor can for example range from 0.5 to 1.5. When provided REDD credits ensure maximum co-benefit maintenance then the offered price for the winning bidder would be increased by the factor 1.5. If the winning bidder only provides the lowest possible co-benefit protection his offered price could be discounted by 0.5.

An alternative approach to use the relative co-benefit performance as criterion for the pricing can be realized. Here, the offered REDD units are distinguished into different tranches according to the provided sustainability co-benefit value points.

After a certain amount of REDD units of the highest tier (determined by a minimum amount of co-benefit value points) has been purchased, the auctioneer lowers the minimum points (and the provided finance) to qualify for the next tier of REDD units in the next auction tranche and collects bids at this lower sustainability co-benefit value level. The IIR continues to lower the points (and finance) until the targeted REDD units are bought or the finance portfolio is exhausted.

For both options where sustainability co-benefits are used for the pricing of REDD credits, the sealed bid second-price auction allows maximizing the total sustainability benefit value of a REDD action. This would shift the incentive structure for REDD policy action designs from the simple maximization of emission avoidance to a more comprehensive approach of both emission-avoidance and ecosystem co-benefit maximization.

The introduced novel design elements of IERSCC for monitoring and RL development and the IIR for auctioning and catalysing REDD credits are interrelated and can help to overcome current methodological and political challenges. Their connections and interdependencies are summarized in Figure 2.

Conclusion

There is general agreement in REDD policy circles that emission reduction units generated by any REDD mechanism under the UNFCCC must be "real" and environmentally integer. Key to the supply of "real" REDD credits is an appropriate reference level against which additional REDD efforts can be measured, and compensation can subsequently be claimed. For compensation mechanisms, appropriate RL are necessary, irrespective of whether REDD credits are supplied to funds, are made fungible to markets or involve any other REDD implementation design.

As was alluded to earlier, a danger exists that if the methodology for setting RL is not carefully designed it will lead to non additional emission reductions and potentially to an inflated supply of REDD credits. There is the inherent problem of generating and exploiting information asymmetries, which countries will want to exploit by increasing the emission levels for their emission reference scenario. Because the "true" REDD effort is poorly observable, individual market agents are inclined to use the information asymmetry to over-report on their individual efforts and the easiest way to inflate reported efforts is to increase the RL. That is why we have proposed the establishment of an International Emission Reference Scenario Coordination Centre (IERSCC), specifically tasked to establish globally consistent national reference emission scenarios based on standardized and consistent data and algorithms, according to the outcomes of the continuing REDD negotiations under the UNFCCC. RL will need to be established in a globally consistent manner in order to address the problems of geographic and sectoral leakage. The issue of leakage is closely linked to the issue of how drivers of deforestation are included in RL and it rapidly becomes highly contextual. For example, RL of one place or country can depend on the actions of REDD by other market participants. In a particular country where forest conversion is due to the expansion of intensive agriculture, REDD

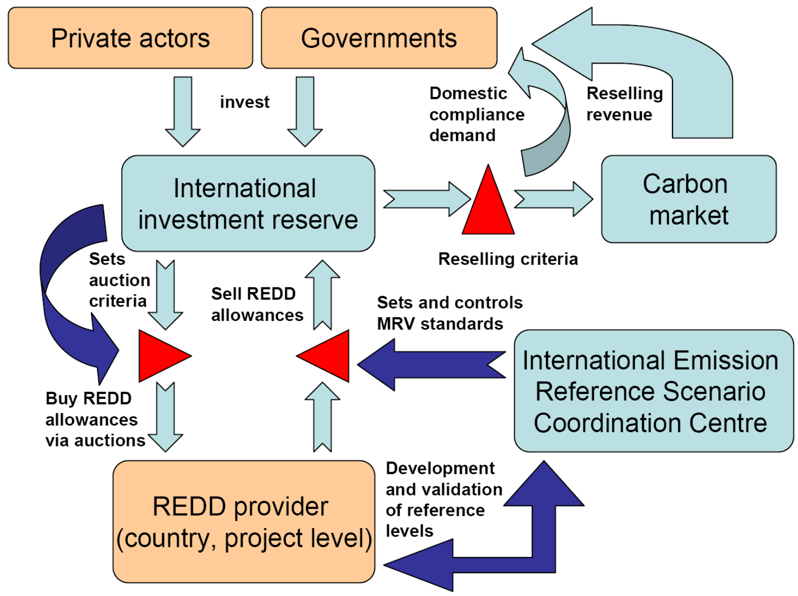

Figure 2
Institutional relationship. Relationship among the International Emission Reference Scenario Coordination Centre (IERSCC) the International Investment Reserve (IIR) and the carbon market under an auctioning approach.

actions in this area can lead to high leakage to other regions/countries. However, if e.g. the driver is extensive cattle-ranching and if REDD measures target the intensification of livestock production systems, then geographic leakage will most likely be small. Thus, RL setting of one country might need to account for the ensemble of global REDD actions, or even more general land-use impacting policies such as biofuel supporting policies.

More realistic reference scenarios would also lead to more transparency and finally to "fairness" in the REDD process. "Real" RL are a precondition for more robust cooperation between parties under the UNFCCC. Asymmetrically inflated RL would lead to windfall profits for the inflating countries, resulting in an unfair allocation of global financial resources dedicated to REDD. Due to its inflated reference emission scenario, country X might receive all of the global REDD resources and country Y would get nothing by imposing a stringent reference scenario and thus loosing competitiveness. However, under a consistent framework of globally harmonized and consistent national reference emission scenarios, countries X and Y would share the globally available REDD resources in a fair manner as they would be compensated for their real efforts.

There are two main problems associated with the asymmetric inflation reference scenario. First, cooperation within tropical countries would be put under threat. Clearly, country Y would try to sabotage negotiations under such conditions, since it would face a loss of revenues from a global REDD mechanism while its competing tropical country would be gaining revenues. Second, REDD credit buyers would face an environmental integrity problem. The entity sourcing REDD credits could *ex-post* be blackmailed for having undermined the environmental integrity of its emission reduction claims and have spent a large share of its resources on REDD hot air.

Besides the prevented information asymmetries, the IERSCC could provide data much cheaper than under pure nationally-based monitoring and earth observation systems. Its associated costs could for example be generated by establishing a tax on sold REDD credits, based on individual donor contributions or by the IIR.

The financing of REDD under an 'International Investment Reserve' would allow the timely provision of large sums for REDD. Sufficient up-front financing can be ensured to tackle deforestation in meaningful quantities, since the IIR allows combining financial resources from national governments targeting market and fund approaches as well as private investments. Details on the management of such IIR still need to be determined, but rich experiences from other study fields exist. The main challenges - similar to the IERSCC - will be to avoid institutional overburdening while at the same time allowing the participation of all relevant stakeholders. The IIR auctioning approach also needs to avoid single country domination such as in the CDM. The participation rules for REDD unit provider should thus take into account their total supply provision to avoid auction domination. For the auctioning mechanism broad participation could be ensured using multiple tranches of finance provision. Subsequent tranches would be lowered in their fixed amount of money to give an incentive to large suppliers for early offers as well as maintaining the option for small (and possibly more expensive) REDD suppliers to participate in the later tranches.

Compliance with environmental and social standards could be ensured through appropriate auditing and possible certification, as an entry condition to participate in the mechanism. Such certification using for example existing REDD standards such as the Climate, Community & Biodiversity Alliance's (CCBA, http://www.climate-standards.org/) could act as a qualifying trait. However, due to heterogeneous priorities and capacities in developing countries, an ambitious standard would most likely overburden the REDD negotiations. Thus, alternatively to a co-benefit qualifying trait a relative quantification of co-benefits as competitive trait provides several advantages. First, it allows maximizing co-benefit provision. But even more important, it can function as additional incentive without excluding REDD providers, which would otherwise fail a high co-benefit standard. We provided alternative options how to incentivize co-benefit performance. The sequential differentiation of tranches according to co-benefit performance would only provide meaningful incentives, if large amounts of REDD units with high co-benefit provision would exist. This however remains speculative. If the co-benefit factor would instead be used as competitive trait, the REDD providers would be incentivized to provide a low unit price and high co-benefit performance without limiting the participation to a specific tranche. The use of the co-benefit factor will also make it harder for REDD providers to speculate on the prices of their co-bidders in each auction, thus limiting the threat of strategic pricing.

What is essential to note is that in such a co-benefit maximising auction design the underlying causes of deforestation and degradation (e.g. poverty) might be attacked more effectively, and would allow for a wide portfolio of REDD implementation instruments. In addition, it needs to be recognized that REDD, if it is purely focused on carbon, will create additional pressure on forests with low carbon stocks such as the Brazilian Cerrado, which is a known biodiversity hotspot. This "biodiversity leakage" effect of REDD within the forest domain needs to be addressed.

To increase the precision of the proposed REDD mechanism with respect to sustainability co-benefit provision, it will be necessary to map with higher precision, and more comprehensively, the ecosystems and societal values *per se*, and agree at the international level on how to quantify co-benefits, such that they could be incorporated into the proposed mechanism. The spatial and temporal deforestation driver data from IERSCC could assist in this task. Besides these more ambitious requirements for the competitive trait, the auction mechanism design should be implemented using robust but simple MRV standards as qualifying criteria to sell REDD units. This is crucial, if sufficient competition should develop, since currently only a handful of countries are "REDD ready". To reach these robust MRV standards REDD readiness funding will be crucial in the coming years. The flexible structure of the IIR will allow early and fluent phasing from such a funding approach towards the proposed investment reserve.

Both Annex I as well as Non-Annex I countries are currently working towards a policy process ensuring that RL are supplied in a transparent, consistent, comparable and accurate manner. It is commonly understood that "real" reference level are a necessary precondition for financial REDD resources to be deployed in a manner that is efficient, effective and, most importantly, distributed among recipients in a fair manner. We argue that an integral and robust REDD policy process ought to be based on independent and globally consistent data compilation, and harmonized computation of appropriate reference scenarios. To achieve this, we advocate the establishment of an 'International Emission Reference Scenario Coordination Centre', as an important part of a robust REDD policy process.

Of similar importance as sound reference levels is the provision of a powerful financing mechanism for REDD, which should not contribute to market flooding but lead to sustained and sustainable investments in forest preservation.

We offer a new financial framework of an 'International Investment Reserve', which enables the timely provision of sufficient financial resources without risking carbon market flooding. The IIR will allow to combine REDD finance generation such as classical market investment and fund approaches. This investment reserve can be used to obtain REDD units from supplier countries under an auctioning approach. This allows to pool risks and uncertainties, and subsequently, to resell these verified credits to the carbon market or use them for national compliance purposes. To avoid market flooding, credits will be banked and the reselling will be constrained by criteria to ensure environmental integrity as well as carbon price floors and caps. This helps to smoothen price volatility.

REDD will not only contribute to mitigating climate change but might also emerge as a major tool to conserve the ecosystem and wider societal values of forests. In this paper, we have explored new ways of how to build "ecosystem and social services" into the carbon economy. Understanding that biodiversity, ecosystem services and other services of forests to society (and the related REDD opportunity costs) are not distributed evenly across the forests of the world, we propose a mechanism design for REDD implementation which allows to maximize carbon and ecosystem co-benefit provision without excluding REDD credit providers.

Consequently, REDD will only be successful in the long term, if it manages the balance between environmental integrity, economic efficiency and political robustness. The REDD mechanism design proposals of two independent REDD institutions, the IERSCC and IIR, introduced in this paper can positively contribute to this endeavour.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

MO had the idea, provided the first draft for the design of the study and critically reviewed the manuscript during each step of production. MH provided the idea for the investment reserve and substantially contributed to several sections of the manuscript, i.e. data analysis and interpretation. FK coordinated the work on this paper and substantially contributed to the analysis and further developing of the ideas. IM provided literature and data and helped drafting paragraphs of this paper. KA, HB, SF, MG, PH, GK, ER and BR provided substantial expert knowledge and ideas during the author's discussions, without which this article could not have been produced. All authors read and approved the final version of the manuscript.

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References

1. Böttcher H, Eisbrenner K, Fritz S, Kindermann G, Kraxner F, McCallum I, Obersteiner M: **An assessment of monitoring requirements and costs of 'Reduced Emissions from Deforestation and Degradation'.** *Carbon Balance and Management* 2009, **4:**7.
2. Strassburg B, Turner RK, Fisher B, Schaeffer R, Lovett A: **Reducing emissions from deforestation--The "combined incentives" mechanism and empirical simulations.** *Global Environmental Change* 2009, **19:**265-278.
3. Mollicone D, Achard F, Federici S, Eva H, Grassi G, Belward A, Raes F, Seufert G, Stibig H-J, Matteucci G, Schulze E-D: **An incentive mechanism for reducing emissions from conversion of intact and non-intact forests.** *Climatic Change* 2007, **83:**477-493.
4. Akerlof GA: **The market for lemons: Quality uncertainty and the market mechanism.** *Quarterly Journal of Economics* 1970, **84:**488-500.
5. Olander LP, Gibbs HK, Steininger M, Swenson JJ, Murray BC: **Reference scenarios for deforestation and forest degradation in support of REDD: A review of data and methods.** *Environmental Research Letters* 2008, **3:**025011.
6. Huettner M, Leemans R, Kok K, Ebeling J: **A comparison of baseline methodologies for 'Reducing Emissions from Deforestation and Degradation'.** *Carbon Balance and Management* 2009, **4:**4.
7. Pistorius T: **REDD from the Conservation Perspective - Pitfalls and opportunities for mutually addressing climate change and biodiversity conservation.** Freiburg, Germany: Institute of Forest and Environmental Policy -Albert-Ludwigs-University Freiburg; 2009:37.
8. Livengood E, Dixon A: **REDD and the effort to limit global warming to 2°C: Implications for including REDD credits in the international carbon market.** Wellington, NZ: KEA 3 (prepared for Greenpeace International); 2009:33.
9. Angelsen A: **Chapter 3: Options for Setting Reference Levels.** In *Reducing Emissions from Deforestation and Forest Degradation (REDD): An Options Assessment Report* Meridian Institute; 2009.
10. Ramankutty N, Gibbs HK, Achard F, Defries R, Foley JA, Houghton RA: **Challenges to estimating carbon emissions from tropical deforestation.** *Global Change Biology* 2007, **13:**51-66.
11. Herold M, Johns T: **Linking requirements with capabilities for deforestation monitoring in the context of the UNFCCC-REDD process.** *Environmental Research Letters* 2007, **2:**045025.
12. Fritz S, McCallum I, Schill C, Perger C, Grillmayer R, Achard F, Kraxner F, Obersteiner M: **Geo-Wiki.Org: The Use of Crowd-sourcing to Improve Global Land Cover.** *Remote Sens* 2009:345-354. 1
13. Hare B, Macey K: **Tropical Deforestation Emission Reduction Mechanism - A discussion paper.** *Greenpeace Report. Greenpeace* 2007:49.
14. Ogonowski M, Helme N, Movius D, Schmidt J: **Reducing Emissions from Deforestation and Degradation: The Dual Markets Approach.** *International Future Actions Dialogue. Center for Clean Air Policy* 2007:26.
15. **REDD - The Basis of a "Carbon Federal Reserve"?** [http://www.cleantechblog.com/2009/05/redd-basis-of-carbon-federal-reserve.html]
16. Schlamadinger B, Ciccarese L, Dutschke M, Fearnside Philip M, Brown S, Murdiyarso D: **Should We Include Avoidance of Deforestation in the International Response to Climate Change?** CIFOR, Bogor, Indonesia; 2005.
17. Grassi G, Monni S, Federici S, Achard F, Mollicone D: **Applying the conservativeness principle to REDD to deal with the uncertainties of the estimates.** *Environmental Research Letters* 2008, **3:**035005.
18. EcoSecurities: **Forecasting the Future Value of Carbon - A Literature Review of Mid- to Long-Term Carbon Price Forecasts.** *Portland, US* 2009.
19. WBGU: **Solving the climate dilemma: The budget approach.** In *Special Report* Berlin: German Advisory Council on Global Change; 2009:65.
20. Ebeling J, Yasué M: **Generating carbon finance through avoided deforestation and its potential to create climatic, conservation and human development benefits.** *Philosophical Transactions of the Royal Society B: Biological Sciences* 2008, **363:**1917-1924.
21. EU Commission: **Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions:**

Addressing the challenges of deforestation and forest degradation to tackle climate change and biodiversity loss. *COM(2008) 645/3 Brussels* 2008:13.
22. Huettner M, Villamor G, Huberman D, Ebeling J, Lehmann S, Mannigel E: **How to get REDD right - Navigating the winding road towards sustainability.** *UNFCCC COP14. Poznan, Poland* 2008.
23. Miles L, Kapos V: **Reducing Greenhouse Gas Emissions from Deforestation and Forest Degradation: Global Land-Use Implications.** *Science* 2008, **320:**1454-1455.
24. Obersteiner M, Rametsteiner E, Nilsson S: **Cap management for LULUCF options.** In *Cap Management for LULUCF Options: An Economic Mechanism Design to Preserve the Environmental and Social Integrity of Forest Related LULUCF Activities Under the Kyoto Protocol* IIASA, Laxenburg, Austria; 2001.
25. Schlamadinger B, Obersteiner M, Michaelowa A, Grubb M, Azar C, Yamagata Y, Goldberg D, Read P, Kirschbaum MU, Fearnside PM, Sugiyama T, Rametsteiner E, Boìwald K: **Capping the cost of compliance with the Kyoto Protocol and recycling revenues into land-use projects.** *ScientificWorldJournal* 2001, **1:**271-280.

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A Global Forest Growing Stock, Biomass and Carbon Map Based on FAO Statistics

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Currently, information on forest biomass is available from a mixture of sources, including in-situ measurements, national forest inventories, administrative-level statistics, model outputs and regional satellite products. These data tend to be regional or national, based on different methodologies and not easily accessible. One of the few maps available is the Global Forest Resources Assessment (FRA) produced by the Food and Agriculture Organization of the United Nations (FAO 2005) which contains aggregated country-level information about the growing stock, biomass and carbon stock in forests for 229 countries and territories. This paper presents a technique to downscale the aggregated results of the FRA2005 from the country level to a half degree global spatial dataset containing forest growing stock; above/below-ground biomass, dead wood and total forest biomass; and above-ground, below-ground, dead wood, litter and soil carbon. In all cases, the number of countries providing data is incomplete. For those countries with missing data, values were estimated using regression equations based on a downscaling model. The downscaling method is derived using a relationship between net primary productivity (NPP) and biomass and the relationship between human impact and biomass assuming a decrease in biomass with an increased level of human activity. The results, presented here, represent one of the first attempts to produce a consistent global spatial database at half degree resolution containing forest growing stock, biomass and carbon stock values. All results from the methodology described in this paper are available online at www.iiasa.ac.at/Research/FOR/.

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1 Introduction

Biomass (the quantity of living plant material) is most abundant in forests. Tropical forests account for 50% of Earth's total plant biomass, although they occur on only 13% of the ice-free land area; other forests contribute an additional 30% of global biomass (Chapin et al. 2002). Knowing the spatial distribution of forest biomass is important for many reasons, including: calculating the sources and sinks of carbon that result from converting a forest to cleared land (and vice versa); and to enable measurement of change through time (Houghton 2005). With respect to the Kyoto Protocol and potential follow up protocols not only information on the spatial distribution of forests is essential, but also its associated biomass. For example, forest biomass may be altered without a change in forest area. Many factors act to alter forest biomass, including selective wood harvest, forest fragmentation, ground fires, shifting cultivation, browsing, grazing and accumulations of biomass in growing and recovering (or secondary) forests (Houghton 2005).

Currently, information on forest biomass is available only from a mixture of sources, including in-situ measurements, national forest inventories, administrative-level statistics, model outputs and biomass distribution derived from regional satellite products. These data tend to be regional or national, based on different methodologies and they are not easily accessible. Although proposals have been made for the use of satellites to address the lack of data (Hese et al. 2005), there are currently few global spatial forest biomass products available for the earth science community. The scarcity of those maps reflects the diffculty to derive such maps. On a regional level attempts to use satellite data for the extrapolation of ground measurements have been made (Laporte 2006).

The currently available maps on global biomass distribution are either relatively old and are only available in the form of a general ecosystems map (Olson et al. 2001) or they are outputs of current global dynamic vegetation models which are still under development with respect to carbon allocation and will need to be improved (Kucharik et al. 2006). Moreover, these maps tend to reflect the long term potential, but do not reflect the current status of human induced activities (Hu et al. 1996). Even though these models are not calibrated in terms of biomass itself, these models are already in use to derive these highly important figures on global biomass emissions (Hoelzemann et al. 2004).

Another map which provides average biomass values per country is the database of the Global Forest Resources Assessment (FRA) produced by the Food and Agriculture Organization of the United Nations (FAO 2005). This dataset contains aggregated country-level information about the growing stock, biomass and carbon stock in forests for 229 countries and territories. However, for use in spatially explicit analysis and modeling, this information is required at a finer level of detail than country level. In addition, many of the countries had diffculties in providing data, creating gaps which prevent global analysis.

The growing stock in yield tables is usually determined by age, stocking degree, yield level and species (Assmann 1970). Shvidenko et al. (2007) are using NPP to describe the yield level. The stocking degree and the rotation period are influenced by human activity. There is a relationship between NPP and biomass and additionally a relationship between biomass and human impact (Keeling and Phillips 2007). By using this relationship a simple but plausible downscaling model is developed. Such an approach is feasible since both NPP as well as human impact are available at least on a half degree resolution.

The technique described here illustrates one plausible way of downscaling the aggregated results of the FRA2005 from the country level to a half degree global spatial dataset containing forest growing stock; above-ground, below-ground, dead wood and total forest biomass; and aboveground, below-ground, dead wood, litter and soil carbon.

Table 1. Used datasets.

Dataset	Values	C/G	Source
Growing stock	m^3/ha	C	FAO (2005)
Biomass stock	Mt	C	FAO (2005)
Carbon stock	MtC	C	FAO (2005)
Forest area	ha	C	FAO (2005)
Country	Country Name	G	CIESIN (2005b)
NPP	3 to 1373 gC/m^2/year	G	Cramer et al. (1999)
Human influence	0–100%	G	CIESIN (2002)
Land area	0–3091 square km	G	CIESIN (2005a)
Forest share	0–100%	G	JRC (2003)

C/G = Information given for country (C) or for grid points (G)

2 Material and Methods

2.1 Used Datasets

A variety of datasets were used in this approach and are listed in Table 1 and described below. The FRA2005 provides global tables containing values on growing stock, biomass and carbon. Growing stock is available in m^3/ha, while biomass stock and carbon stock are in Mt per country. Biomass is given as fractions of above-ground, below-ground, dead-wood and total biomass. Carbon is given as above-ground carbon, below-ground carbon, carbon in dead wood, carbon in litter and soil carbon. The biomass stock and carbon stock were recalculated into values per hectare by dividing the given value by the forest area also given in the FRA2005.

In all cases, the number of countries providing data in the FRA2005 is incomplete, although the majority of forest area is found in relatively few countries. The last column of Table 4 shows the number of countries with available values for that parameter. In particular, the carbon pools in litter and soil were reported by less than 50 countries. Of the 151 countries that reported forest biomass: 87 have used the IPCC good practice guidance biomass expansion factors exclusively; 41 have used the IPCC factors in combination with factors from other sources; 13 have used national data – either direct estimates or national expansion factors; 5 have used factors/models from FAO and FAO/UNECE publications; and 5 are based on expert estimates FAO (2005). In the FRA tables, values of above ground biomass can be found for 146 countries. In the calculations only 145 values have been used as one country was too small to represent at least one balf-degree grid.

The NPP data set contains modeled annual net primary production (NPP) for the land biosphere from seventeen different global models (Cramer et al. 1999). This data set was created in the mid-1990s with 17 models available at that time. It uses data from Remote Sensing Based Models, Models of Seasonal Biogeochemical Fluxes and Models of Process and Pattern (Function and Structure).

The human influence map was taken from CIESIN (2002). Nine global data layers were used to create this global "human footprint" map. The layers describe human population pressure (population density/population settlements), human land use and infrastructure (built up areas, night-time lights, land use/land cover), and human access (coastlines, roads, railroads, navigable rivers).

The forest share of a country was taken from FAO (2005) and the forest share on a grid was taken from the global land-cover product GLC2000 (JRC 2003). Pure forest classes are assumed to be covered 100% by forest, the GLC2000 classifications "Mosaic: Tree Cover / Other natural vegetation" have 50% and "Mosaic: Crop-land / Tree Cover / Other natural vegetation" have 20% tree coverage. The tree coverage for the 0.5×0.5 degree grid was calculated by summing up the tree cover of the given 1×1 square kilometer grid of GLC2000 on the area of 0.5×0.5 degree grid and dividing it by the total grid area.

According to the FRA2005, the total global forest area equates to 39 520 250 km^2. In comparison, using the satellite derived GLC2000 (all classes with tree cover excluding burnt area), we calculated a total global forest area of 39 794 530 km^2. The global difference is below 1% and the probability that there is no difference between them, done with a country-wise pairwise t-test, is 94% (see Table 4).

The difference between the forest cover given in the FRA2005 for each country and a half degree aggregated map produced from the GLC2000 show some scatter (Fig. 1). This difference can occur for several reasons. One reason is, that different forest definitions and threshold values (e.g. canopy coverage %) are applied. Another reason is that the grid size of 0.5°×0.5° does not adequately represent the country borders. This obviously has a greater impact on smaller countries.

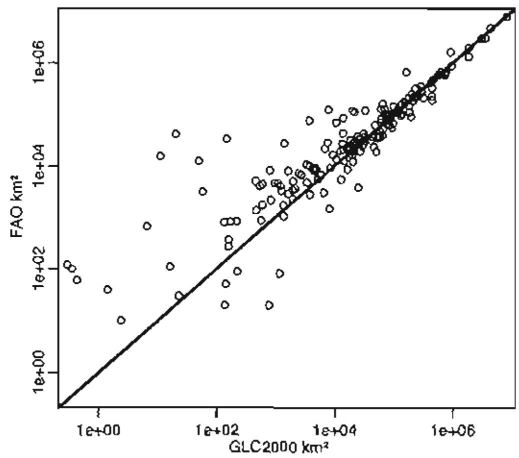

Fig. 1. Forest area of countries given in FAO (2005) and calculated from JRC (2003).

2.2 Methodology to Derive Above Ground Biomass

A number of studies have outlined that both biomass and NPP are related in the sense that both are dependent on water availability, temperature and the availability of nutrients (Koch et al. 2004, Richards and Brack 2004). This relationship was found to be either linear (Whittaker and Likens 1973) for the temperate zone or quadratic, as a recent study suggests that aboveground biomass plateaus in mid to high NPP levels (Keeling and Phillips, 2007). We have used a linear relationship between NPP values given in Cramer et al. (1999) and biomass. Furthermore, it has been suggested that biomass accumulation is clearly influenced by human activity (Keeling and Phillips 2007). By applying thinning and clear cut management, the growing stock of a managed forest is lower than the growing stock of pristine forests. E.g. unmanaged spruce forests in central Europe have an age of more than 400 years when they reach senescence. Managed forests are harvested with an age around 100 years. During the ages from 100 to 400 years, spruce forests have a high growing stock which will lead to higher average values in unmanaged forests. On the other hand protecting forests against damage (e.g. fire, insects) will lead to higher amounts of biomass in managed forests.

Based on such findings we assume that if biomass is known on a country level, it can be downscaled based on the two factors NPP and human impact. Biomass as described here is therefore a function of NPP and human impact expressed as:

$$\text{Biomass} = c_0 \times \text{NPP} \times \text{Human} \qquad (1)$$

Where c_0 = a factor describing the slope between NPP, human influence (Human) and the estimated Biomass (A list of all abbreviations is given in Table 2). An increasing NPP will cause a linear increase of the biomass. An increasing human influence will cause a decrease of the biomass. We assume, that managed forests have half of the biomass than forests without human influence. So human influence values have to be scaled that 1 represents areas with 100% human activity and 2 represents areas with no human activity.

The biomass of a certain grid cell (Grid value$_i$) is calculated with the biomass given in FRA2005 for the country in which the grid is located (Country value$_j$) multiplied by the NPP (NPP$_i$) and the human influence (Human$_i$) of the grid and divided with the average product of NPP and human influence for grids located in this country. The average is calculated by summing up the product of NPP, human influence, grid area (A$_i$) and forest share (ForShare$_i$) for all grids from a country and dividing this by the sum of grid area multiplied with forest share.

Equation 2 was used for country (j) to modify the former constant country value per hectare, so that the average value per country is still the same but on grids with a higher NPP and a lower human activity the value will be higher than on grids with a low NPP and high human activity. This approach is used to calculate all variables (i. e. growing stock, litter, soil).

$$\text{Grid value}_i = \frac{\text{Country value}_j \cdot \text{NPP}_i \cdot \text{Human}_i}{\frac{\sum_{l \in L_j} \text{NPP}_l \cdot \text{Human}_l \cdot A_l \cdot \text{ForShare}_l}{\sum_{l \in L_j} A_l \cdot \text{ForShare}_l}} \qquad (2)$$

Table 2. Symbols used in equations.

A	Grid area (km^2)
Biomass	Forest biomass (t/ha)
Country value	Given value per country (e.g. tC/ha)
c_x	Coefficients
ForShare	Forest share (1)
Grid value	Downscaled value (e.g. tC/ha)
Human	Human influenee (1)
Index i	Index for grid cells
Index j	Index for countries
Index l	Index for grid cells located in country j
L_j	Array of grid cells located in country j
m^3	Growing stock (m^3/ha)
NPP	Net primary productivity (gC/m^3/ Year)

2.3 Filling Missing Values

Since the FAO datasets are incomplete we estimate values for grids which contain forest but are in a country where the FRA2005 gives no value. This was performed with a linear regression shown in Eq. 3.

$$\text{Grid value}_i = c_1 + c_2 \times \text{NPP}_i \times \text{Human}_i + c_3 \times \text{NPP}_i + c_4 \times \text{Human}_i + c_5 \times m^3_i \qquad (3)$$

The value of a certain grid (Grid value$_i$) is calculated with NPP × Human, NPP, human activity and growing stock (m^3) of grid i. As only 147 countries provided a growing stock value, using the growing stock (m^3) in Eq. 3 it is not possible to create a growing stock map. Therefore only the NPP and human influence values are used to calculate the growing stock. The parameterization of Eq. 3 was done with grid cells from countries where FRA2005 gives values for them. The number of used grids and coefficients can be found in Table 3. Afterwards Eq. 3 was used on grid cells containing forest but located in countries where FRA2005 gives no value.

Statistics have been performed using R (R Development Core Team 2005) and spatial analysis was performed using the GIS software GRASS (GRASS Development Team, 2006).

Table 3. Parameters to fill up grids with Eq. 3 where no country value is given.

Value	c_1	c_2	c_3	c_4	c_5	r^2	sd	n
m^3	136	0.211	−0.253	−60.8	–	0.44	±44.2 m^3/ha	57 652
BmAbove	−43.1	0.0191	0.0431	17.8	0.679	0.76	±32.9 t/ha	53 038
BmBelow	−2.11	0.0220	−0.0135	–	0.142	0.69	±9.9 t/ha	52 998
BmDead	−46.4	−0.0336	0.0582	28.6	0.142	0.41	±9.0 t/ha	48 311
BmTotal	−92.6	−0.0299	0.154	46.8	0.969	0.76	±44.1 t/ha	48 479
CAbove	−23.0	0.00598	0.0258	9.74	0.346	0.75	±16.9 tC/ha	53 038
CBelow	−1.17	0.0116	−0.00679	–	0.0637	0.72	±4.6 tC/ha	52 992
CDead	−23.2	−0.0172	0.0297	14.3	0.0703	0.41	±4.5 tC/ha	48 278
CLitter	10.2	−0.00978	0.0127	−4.17	0.0560	0.29	±4.1 tC/ha	30 130
CSoil	207	0.211	−0.446	−78.0	0.615	0.19	±57.0 tC/ha	27 823

c_x = Significant coefficients ($\alpha = 0.05$); r^2 = Correlation; sd = Standard deviation; n = Number of grids used for parameterization

3 Results

In Fig. 3 the steps taken from the input maps to the derived carbon map is shown. Fig. 3D shows the downscaled map of carbon/ha in forests, which is a result of using Eq. 2 with the datasets: country values of tC/ha (A) from FAO (2005), human footprint (B) from CIESIN (2002) and NPP (C) from Cramer et al. (1999). In some cases country borders are visible and some regions have no value. It can also be seen, that carbon decreases in regions where the NPP is low e.g. if you go north in Siberia the values will decrease. The influence of human activity can be observed e.g. in the region north India, Nepal and Bhutan where a black line, showing high values, is caused by low human influence and higb NPP values.

Regions without a value are calculated using Eq. 3. This step can be seen from Fig. 3D to E. This procedure seems to function well as most of the borders between missing and given regions are not visible in Fig. 3E and the correlation coefficients shown in Table 3 are many times in the range of $r^2 = 0.7$.

For some users the map of biomass per hectare of forest (E) will suffice. Others may want to know the values per grid. To satisfy these needs the land area (F) and the forest share (G) of a grid were overlaid. These steps are shown in Fig. 3E–H. Fig. 3H shows the carbon in forests on a certain grid. On this map only a few country borders can be seen. E.g. the border between Malaysia and Indonesia can still be seen, the borders around Egypt disappear.

Growing stock, biomass (above-ground, below-ground, dead wood) and carbon (above-ground, below-ground, dead wood, litter) and soil carbon, provided in the FAO (2005) at the country level, have been downscaled to a spatially explicit global half degree grid using exactly the same approach.

Fig. 2 compares above ground forest carbon identified in the FRA2005 with the results of this paper. Differences are caused by different forest cover between the FRA2005 and GLC2000 and the coarse 0.5°×0.5° grid resolution. Pictures of the other carbon pools look quite similar to Fig. 2. Small countries tend to capture not enough grids to represent their area. This can be observed

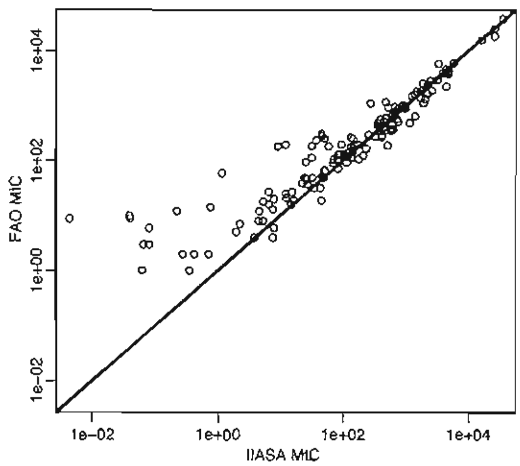

Fig. 2. Above ground carbon for countries given in FAO (2005) and calculated.

Table 4. Comparison of Model and FAO values.

Value	Σ	Δ	p	n
Forest Area	39 794 530 km^2	0.69%	0.94	221
m^3	465 992 Mm^3	5.25%	0.19	147
BmAbove	472 086 Mt	2.25%	0.66	145
BmBelow	125 058 Mt	–0.44%	0.94	140
BmDead	82 823 Mt	–0.79%	0.86	104
BmTotal	676 911 Mt	1.65%	0.75	110
CAbove	233 764 MtC	2.43%	0.63	143
CBelow	61 959 MtC	–0.19%	0.97	138
CDead	41 000 MtC	–0.47%	0.91	102
CLitter	22 765 MtC	1.65%	0.45	48
CSoil	397 870 MtC	1.79%	0.51	43

Σ = Global sum from the IIASA model; Δ = Difference between IIASA model and FAO table 100 · (IIASA – FAO) / IIASA;
p = Probability that the difference between IIASA model and FAO is 0;
n = Number of compared countries

in Figs. 1 and 2 where FAO gives higher values for small countries. The reason for this is that countries need to occupy the majority of a grid to own the whole grid.

In Table 4 the results from the method described in this paper (total values) are presented, along with the difference compared to the values of the original FRA2005 tables. The total forest area is 39 800 000 km^2, which is 0.69% above the given values of 221 countries from FRA. The global growing stock is 466×10^9 m^3 which is 5.25% above the given values from 147 countries from FRA. The above ground biomass is 472×10^9 t,

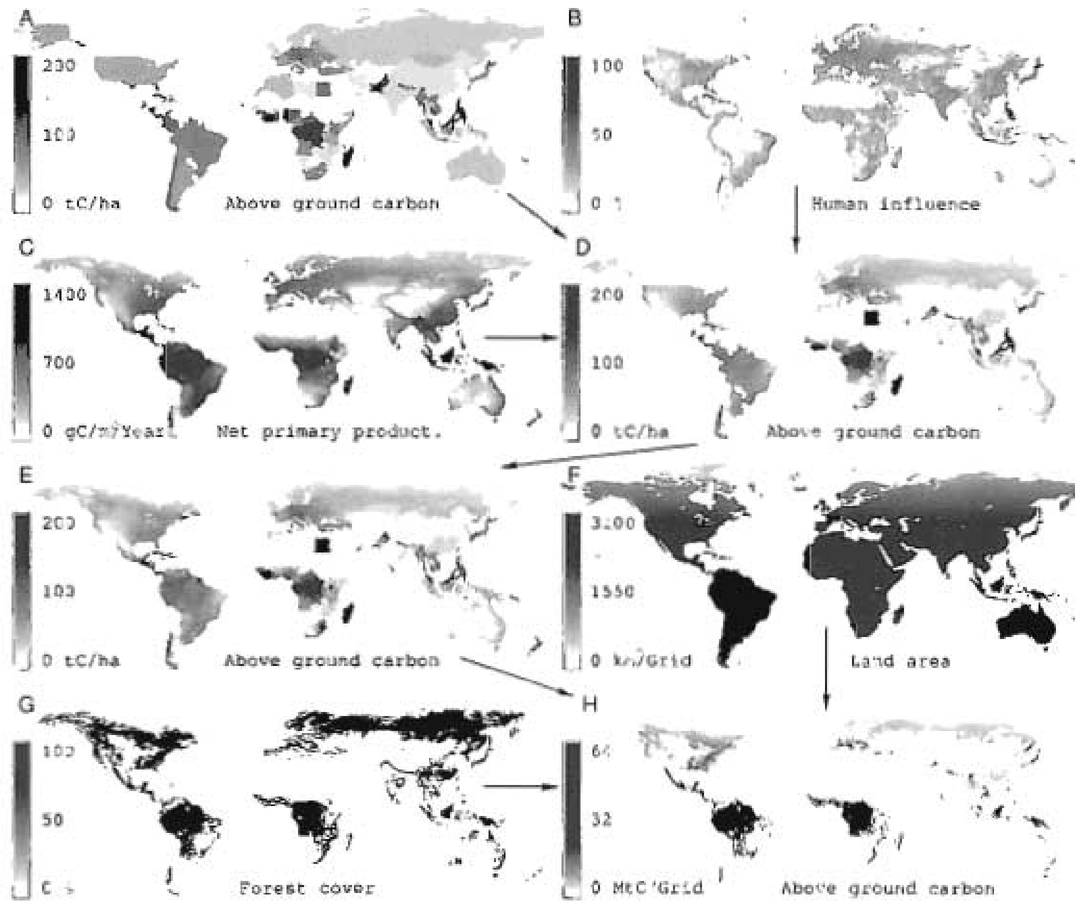

Fig. 3. Downscaling county values to grid values. A. Country values of above ground tC/ha in forests – some countries don't provide values; B. Human footprint; C. NPP in gC/m^2/year; D. tC/ha in forests; E. tC/ha in forests – completed; F. Land area in km^2/half degree Grid; G. Forest share; H. MtC/Grid.

the below ground biomass 125×10^9 t, the dead biomass 83×10^9 t and the total biomass 677×10^9 t. Here the total biomass is not equal to the sum of above ground, below ground and dead biomass because the total biomass was generated from the values for total biomass given in the FRA2005 tables. The above ground carbon is 234×10^9 tC, the below ground carbon 62×10^9 tC, the carbon in dead wood 41×10^9 tC, the carbon in litter 23×10^9 tC and the carbon in forest soils 398×10^9 tC.

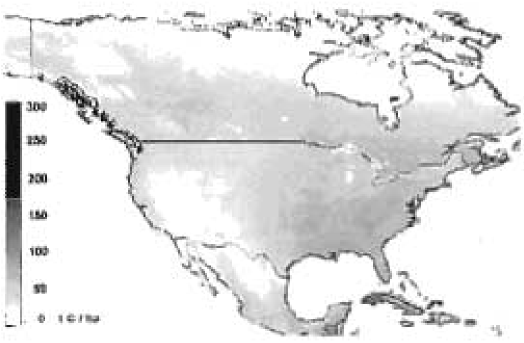

Fig. 4. Above ground Carbon Map – US (tC/ha in forests).

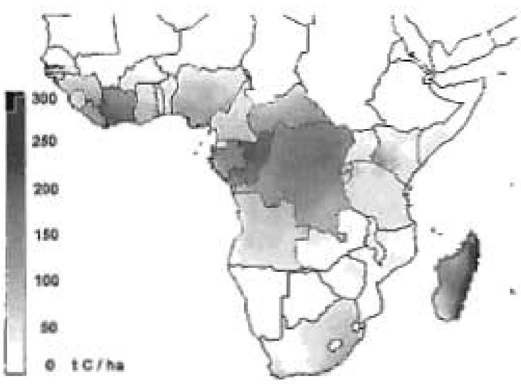

Fig. 5. Above ground Carbon Map – Central Africa (tC/ha in forests).

4 Discussion and Conclusion

The significance of forest area as a single indicator of forest development has often been overemphasized – growing stock and carbon storage may be considered equally important parameters (FAO, 2005). The results presented here represent one of the first attempts to produce a consistent global spatial database at half degree resolution containing forest growing stock, biomass and carbon stock values, based on the FRA2005. The approach makes some simple assumptions and will not be error free. However, this method will produce maps which are useful for current applications related to biomass burning emissions, carbon cycle or deforestation issues.

In some areas country borders can still be seen. This could have been reduced by using a smoothing function on the produced maps but this would also change the average country values so that they are not coincident with the FRA2005. The methods used here depend heavily on the accuracy of FAO stats. In Fig. 4, which shows carbon above ground, the country borders between USA, Canada and Mexico are not visible, whereas in Fig. 5 many country borders of Africa can be identified. This can be a realistic phenomena since in different countries, in particular in Europe, forest management differs and therefore carbon stocks vary. However in some countries within Africa the borders could also be artefacts and do not reflect different forest management.

Even though the FRA2005 database provides one of most consistent and current global datasets on forest parameters, many countries have difficulty providing data on biomass and carbon stocks, and the quality of the information provided is variable (FAO 2005). Large areas in some case have no value.

The presented methodology is a first attempt to downscale the FAO biomass data which is reported on a country level to a resolution of 0.5 degrees by using the relationship between biomass, NPP and human impact. Clearly there are shortcomings in the method due to a number of factors. The relationship between NPP and above-ground Biomass is not clear since it may be linear, quadratic or another relationship, depending on the region itself. The same applies for the other biomass and carbon fractions (i.e. biomass below ground, dead wood and total wood, carbon above, below ground, dead wood and litter) and soil carbon. Peat lands, for instance, store huge amounts of carbon in their soil as a result of long term accumulation and don't show high NPP rates. As we are only describing carbon pools in forest, the extremes of peat lands won't affect the results of this paper. Nevertheless it should be mentioned, that especially the soil values may not have such a tight relation to NPP as the above ground biomass has. Soil and litter values are based on few country values from FAO. This may indicate that these values are hard to gather and have not the quality like values of growing stock. The uncertainty of the estimated values for a grid depends on the quality of the FRA-values, the forest cover map, the linearity of NPP and human activity to the estimated values, the human activity map and the NPP map. The grid values summarized by country are similar to the FAO values and the quality will be in the same range.

This method is based on national FAO statistics which were derived from inventory data. Such a method has the advantage over dynamic vegetation models that it gives quite realistic estimates and is not prone to unrealistically high biomass accumulations – often the output of current global dynamic vegetation models, where the biomass module is still under development.

Techniques applied in this paper attempt to account for some of these inconsistencies and missing values in the data through a combination of other spatial datasets and regression analysis. This has resulted in a transparent methodology which delivers a suite of forest parameters in demand by the earth science community. These products could prove beneficial for comparison with biomass maps derived from future FRAs and results of DGVMs and biomass maps derived from future satellite missions.

Currently the datasets we could use to validate these results are sparse, but with sub-national statistics from FAO becoming available we could improve our methodology. Since the Earth science community is eager to use global higher resolution datasets, they are made available to be used in a number of applications. Users of these datasets do however have to be aware of the current limitations and shortcomings and the data should be used with care.

All resultant datasets (i.e. growing stock, biomass and carbon) from the methodology described in this paper are available online at www.iiasa.ac.at/Research/FOR/.

Acknowledgements

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References

Assmann, E. 1970. The principles of forest yield study. Pergamon.

Chapin, F., Matson, P. & Mooney, H. 2002. Principles of terrestrial ecosystem ecology. Springer.

CIESIN. 2002. Last of the Wild Project, Version 1 (LWP-1): Global Human Footprint. Dataset (Geographic). Wildlife Conservation Society (WCS) and Center for International Earth Science Information Network (CIESIN), Palisades, NY. URL http://www.ciesin.org/wild_areas/.

CIESIN. 2005a. Center for International Earth Science Information Network (CIESIN), Columbia University; and Centro Internacional de Agricultura Tropical (CIAT). Gridded Population of the World, Version 3 (GPWv3): Land Area Grids. Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University. URL http://sedac.ciesin.columbia.edu/gpw.

CIESIN. 2005b. Center for International Earth Science Information Network (CIESIN), Columbia University; and Centro Internacional de Agricultura Tropical (CIAT). Gridded Population of the World, Version 3 (GPWv3): National Boundaries. Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University. URL http://sedac.ciesin.columbia.edu/gpw.

Cramer, W., Kicklighter, D.W., Bondeau, A., Moore III, B., Churkina, G., Nemry, B., Ruimy, A., Schloss, A. L. & the Participants of the Potsdam NPP Model Intercomparison. 1999. Comparing global models of terrestrial net primary productivity (NPP): overview and key results. Global Change Biology 5: 1–15. URL http://islscp2.sesda.com/ISLSCP2_1/html_pages/groups/carbon/model_npp_xdeg.html.

FAO. 2005. Global Forest Resources Assessment 2005, Progress towards sustainable forest management. Vol. 147 of FAO Forestry Paper. Food and Agriculture Organization of the United Nations, Rome.

GRASS Development Team. 2006. Geographic Resources Analysis Support System (GRASS GIS) Software. ITC-irst, Trento, Italy. URL http://grass.itc.it.

Hese, S., Lucht, W., Schmullius, C., Barnsley, M., Dubayah, R., Knorr, D., Neumann, K., Riedel, T. & Schröter, K. 2005. Global biomass mapping for an improved understanding of the CO_2 balance – the

Earth observation mission Carbon-3D. Remote Sensing of Environment 94: 94–104.

Hoelzemann, J.J., Schultz, M.G., Brasseur, G.P., Granier, C. & Simon, M. 2004. Global Wildland Fire Emission Model (GWEM): Evaluating the use of global area burnt satellite data. Journal of Geophysical Research 109.

Houghton, R.A. 2005. Aboveground forest biomass and the global carbon balance. Global Change Biology 11(6): 945–958. URL http://www.blackwell-synergy.com/doi/abs/10.1111/j.1365-2486.2005.00955.x.

Hu, H., Shibasaki, R. & Box, E.O. 1996. Generation of global terrestrial biomass map by integrating satellite data and carbon dynamics model. GIS-development. URL http://www.gisdevelopment.net/aars/acrs/1996/ts12/ts12009.asp.

JRC. 2003. The global land cover map for the year 2000. GLC2000 database, European Commision Joint Research Centre. URL http://www.gem.jrc.it/glc2000.

Keeling, H.C. & Phillips, O.L. 2007. The global relationship between forest productivity and biomass. Global Ecology and Biogeography 16(5): 618–631.

Koch, G.W., Sillett, S.C., Jennings, G.M. & Davis, S.D. 2004. The limits to tree height. Nature 428(6985): 851–854.

Kucharik, C.J., Barford, C.C., El Maayar, M., Wofsy, S.C., Monson, R.K. & Baldocchi, D.D. 2006. A multiyear evaluation of a Dynamic Global Vegetation Model at three AmeriFlux forest sites: Vegetation structure, phenology, soil temperature, and CO_2 and H_2O vapor exchange. Ecological Modelling 196(1–2): 1–31.

Laporte, N. 2006. Mapping the changing forests of Africa. Supporting Earth System Science. NASA. p. 24–35. URL http://nasadaacs.eos.nasa.gov/articles/2006/2006_africa.html.

Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P. & Kassem, K.R. 2001. Terrestrial ecoregions of the world: a new map of life on earth. BioScience 51(11): 933–938.

R Development Core Team. 2005. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. URL http://www.R-project.org.

Richards, G.P. & Brack, C. 2004. A continental biomass stock and stock change estimation approach for Australia. Australian Forestry 67(4): 284–288.

Shvidenko, A., Schepaschenko, D., Nilsson, S. & Bouloui, Y. 2007. Semi-empirical models for assessing biological productivity of northern Eurasian forests. Ecological Modelling 204(1–2): 163–179.

Whittaker, R.H. & Likens, G.E. 1973. Carbon and the biosphere. In: Woodwell, G. & Pecan, E. (eds.). Carbon in the Biota: proceedings of the 24th Brookhaven symposium in biology, Upton, N.Y., May 16–18, 1972. Technical Information Center, U.S. 738 Atomie Energy Commission, Washington. p. 281–302.

Total of 22 references

Global cost estimates of reducing carbon emissions through avoided deforestation

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Tropical deforestation is estimated to cause about one-quarter of anthropogenic carbon emissions, loss of biodiversity, and other environmental services. United Nations Framework Convention for Climate Change talks are now considering mechanisms for avoiding deforestation (AD), but the economic potential of AD has yet to be addressed. We use three economic models of global land use and management to analyze the potential contribution of AD activities to reduced greenhouse gas emissions. AD activities are found to be a competitive, low-cost abatement option. A program providing a 10% reduction in deforestation from 2005 to 2030 could provide 0.3–0.6 Gt (1 Gt = 1 × 10^5 g) $CO_2 \cdot yr^{-1}$ in emission reductions and would require \$0.4 billion to \$1.7 billion·yr^{-1} for 30 years. A 50% reduction in deforestation from 2005 to 2030 could provide 1.5–2.7 Gt $CO_2 \cdot yr^{-1}$ in emission reductions and would require \$17.2 billion to \$28.0 billion·yr^{-1}. Finally, some caveats to the analysis that could increase costs of AD programs are described.

carbon sequestration | climate change | reducing emissions from deforestation and ecosystem degradation (REDD) | marginal cost | tropical forest

Tropical deforestation is considered the second largest source of greenhouse gas emissions (1) and is expected to remain a major emission source for the foreseeable future (2). Despite policy attention on reducing deforestation, ≈13 million ha·yr^{-1} of forests continue to be lost (3). Deforestation could have the effect of cooling the atmosphere (4), but it also leads to reductions in biodiversity, disturbed water regulation, and the destruction of livelihoods for many of the world's poorest (5). Slowing down, or even reversing, deforestation is complicated by multiple causal factors, including conversion for agricultural uses, infrastructure extension, wood extraction (6–9), agricultural product prices (10), and a complex set of additional institutional and place-specific factors (11).

Avoided deforestation (AD) was included alongside afforestation as a potential mechanism to reduce net global carbon emissions in the Kyoto Protocol (KP), but until recently, climate-policy discussions have focused on afforestation and forest management. Discussions about new financial mechanisms that include AD provide optimism for more effective synergies between forest conservation and carbon policies (11–14). In 2005, Papua New Guinea and Costa Rica proposed to the United Nations Framework Convention on Climate Change that carbon credits be provided to protect existing native forests (15). The proposal triggered a flurry of discussion on the topic. Soares-Filho *et al.* (16), for example, suggest that protecting ≈130 million ha of land from deforestation in the Amazon could reduce global carbon emissions by 62 Gt (1 Gt = 1 × 10^{15} g) CO_2 over the next 50 years.

Although the potential for AD activities to help mitigate climate change is widely acknowledged (16, 17), there is little information available on what the costs might be globally. This article uses three different global forestry and land-use models to estimate carbon supply functions for emission reductions from AD activities. The use of global models is preferred in the case of climate mitigation with land use for two reasons. First, differences across regions in the carbon content of forests, opportunity costs of land, and the costs of access can have important implications for costs. Second, large-scale adjustments, which are likely with policies to reduce deforestation, will affect prices globally. These global changes need to be considered when estimating supply functions (marginal costs) for emission reductions. In addition to being global, the models in this article are intertemporal, taking into account changes that occur over time, such as incentives for deforestation (e.g., demand for agricultural land depending on changes in population, income, and technology). Although agriculture is not explicitly modeled, our models do include different scenarios for agricultural land demand.

Comparing results from several models allows us to assess the sensitivity of results with respect to the use of different methods, datasets, assumptions about future markets, and other potentially important factors (carbon content of forests, interest rates, risk, etc.). Although we do not develop confidence intervals, the results provide a set of estimates that can help policy makers understand the potential cost range of AD.

Table 1. Average carbon per ha and number of ha for tropical forests in the three models used in this analysis

	t C/ha (million ha)		
Model	Central and South America	Africa	Southeast Asia
GTM	106 (913)	100 (352)	132 (202)
DIMA	86.4 (842)	87.7 (684)	74.7 (181)
GCOMAP	97.2 (965)	54.6 (650)	48 (286)

Marginal Cost Curves for AD

The three models used here are the Dynamic Integrated Model of Forestry and Alternative Land Use (DIMA) (18, 19), the Generalized Comprehensive Mitigation Assessment Process

Author contributions: G.K., M.O., B. Sohngen, J.S., and K.A. designed research; G.K., M.O., B. Sohngen, and J.S. performed research; G.K., M.O., B. Sohngen, and J.S. contributed new reagents/analytic tools; G.K., M.O., B. Sohngen, J.S., K.A., and E.R. analyzed data; and G.K., M.O., B. Sohngen, J.S., K.A., B. Schlamadinger, S.W., and R.B. wrote the paper.

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Table 2. Average annual ha deforested and carbon emitted as a result between 2005 and 2030

	Million ha·yr^{-1} (Gt CO_2·yr^{-1})			
Model	Central and South America	Africa	Southeast Asia	Global
GTM	4.84 (1.86)	4.58 (1.72)	2.23 (1.07)	11.65 (4.69)
DIMA	3.62 (1.15)	4.98 (1.61)	1.14 (0.31)	10.60 (3.22)
GCOMAP	4.31 (1.57)	5.99 (1.37)	1.90 (0.38)	12.20 (3.31)

Model (GCOMAP) (20, 21), and the Global Timber Model (GTM) (22, 23). A brief description of each model follows, but a more detailed discussion can be found in supporting information (SI) *Appendices 1–3*. DIMA assesses land-use options in agriculture and forestry in 0.5°-grid cells across the globe. The model predicts deforestation in forests where land values are greater in agriculture than in forestry and, vice versa, afforestation of agricultural and grazing lands where forestry values exceed agricultural ones. GCOMAP is a dynamic partial equilibrium model that analyzes afforestation in short- and long-run species and reductions in deforestation in 10 world regions. GTM is a dynamic optimization model that optimizes the land area, age class distribution, and management of forestlands in 250 timber types globally. Although the model also deals with afforestation and biofuels as mitigation options, this analysis focuses on results for AD.

To estimate the costs of reduced emissions from AD, each model must generate a baseline projection of future deforestation. The baseline is assumed to occur when AD carbon prices are \$0 t^{-1} CO_2. Each model's baseline embeds model-specific assumptions about future changes in economic conditions, *inter alia* population, technology, and trade. The economic assumptions for each model are described in detail in *SI Appendices 1–3*. In addition, carbon emissions from deforestation will depend on assumptions about the quantity of carbon in forest biomass (Table 1).

Different economic and biological assumptions cause the three models to present variable deforestation and carbon-emission projections (Table 2). Estimated deforestation fluctuates over time between 2005 and 2030, but Table 2 presents only the average. GCOMAP estimates the largest area deforested by 2030. GTM projects a smaller area of land deforested, but a larger emission of carbon because that model assumes the largest aboveground storage of carbon per ha. DIMA shows the lowest emission, because of both lower loss projections and lower carbon content assumptions in Latin America.

To determine the marginal costs of carbon storage resulting from AD, additional simulations are conducted with the three models assuming constant carbon prices ranging from \$0 t^{-1} CO_2 to \$100 t^{-1} CO_2. Higher carbon prices will induce the models to allocate more land to forests, and consequently less deforestation will occur. Reductions in carbon emissions from AD are obtained by comparing baseline emissions with the emission path when AD is compensated. The models project results for a longer period, but we present results here only for 2005–2030.

Marginal cost curves, with annual CO_2 emissions reduced on the *x* axis and the carbon price on the *y* axis, are shown for each

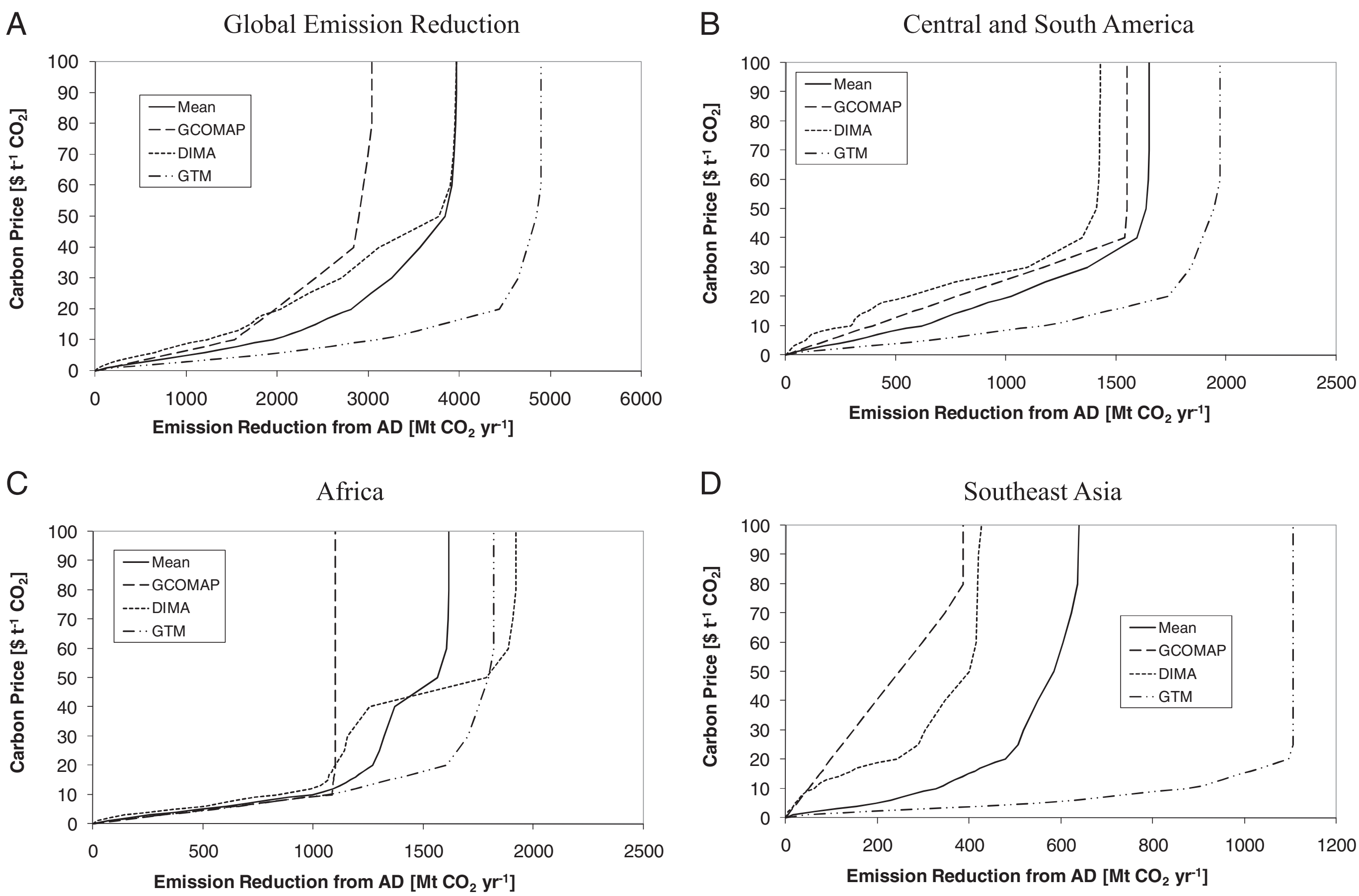

Fig. 1. Marginal costs in 2010 of emissions reductions with AD activities in three regions with predictions of the three models. (*A*) Global emission reduction. (*B*) Central and South America. (*C*) Africa. (*D*) Southeast Asia.

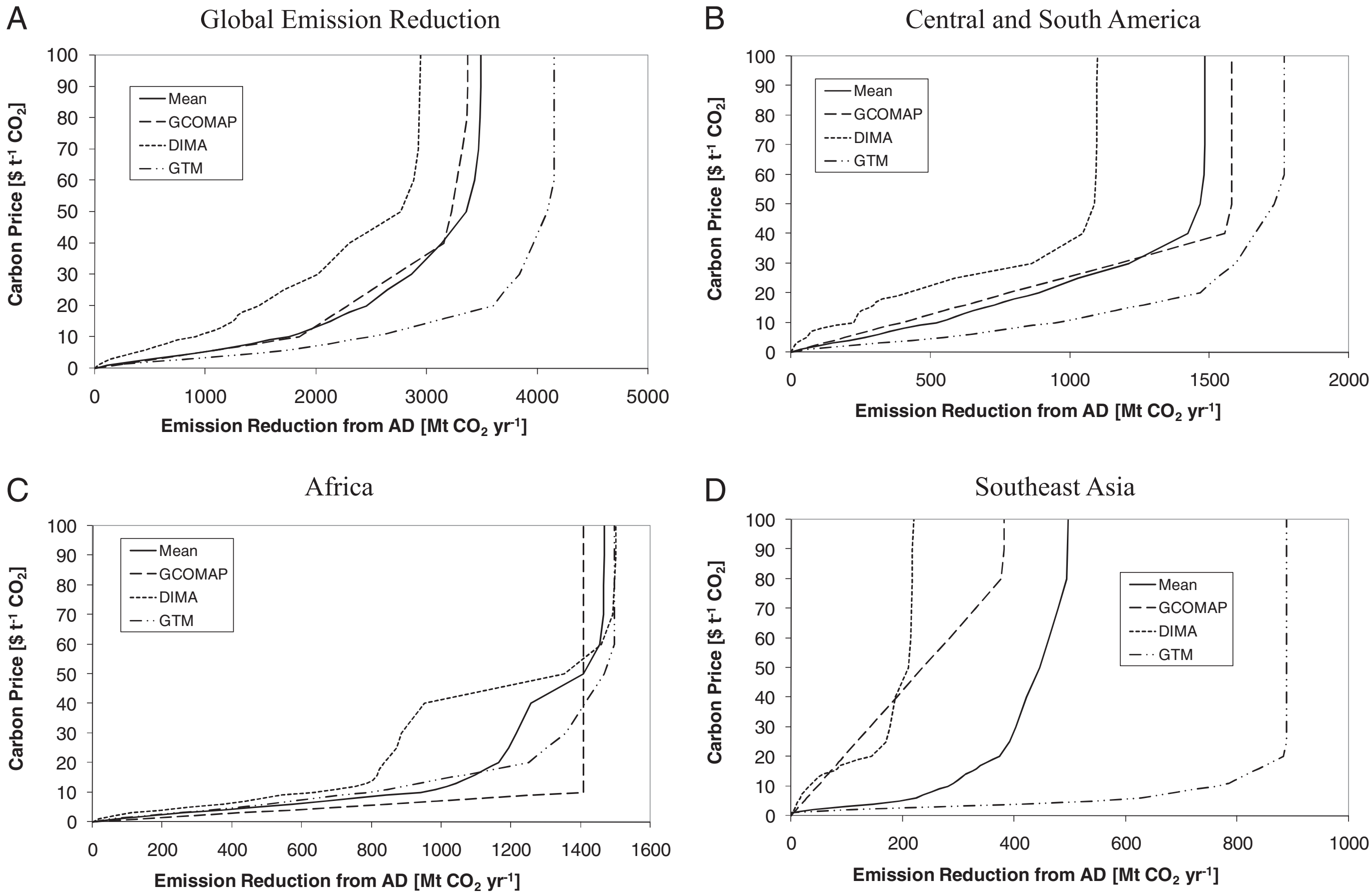

Fig. 2. Marginal costs in 2020 of emissions reductions with AD activities in three regions with predictions of the three models. (*A*) Global emission reduction. (*B*) Central and South America. (*C*) Africa. (*D*) Southeast Asia.

model for 3 years [2010 (Fig. 1), 2020 (Fig. 2), and 2030 (Fig. 3)]. Forest owners would maintain land with the lowest-valued alternative uses (lowest conservation opportunity costs) in forests at the lowest carbon prices, whereas progressively higher carbon prices are required for land with higher opportunity costs.

The results generally indicate that substantial emission reductions can be accomplished over the entire 25-year period examined. For \$20 t^{-1} CO_2, the models project that the average global emission reduction from AD activities between 2005 and 2030 would be in the range of 1.6 to 4.3 Gt $CO_2 \cdot yr^{-1}$. For higher prices (\$100 $t^{-1} CO_2$), the models project emission reductions of 3.1–4.7 Gt $CO_2 \cdot yr^{-1}$. The time path of marginal costs suggests that the low-cost emission reductions occur earlier on. At \$100 t^{-1} CO_2, the emission reduction averaged for all three models in 2010 is 4.0 Gt $CO_2 \cdot yr^{-1}$, but this falls to 3.1 Gt $CO_2 \cdot yr^{-1}$ by 2030. Marginal costs tend to rise over time because the lowest-cost opportunities are adopted first and rates of deforestation decline, while later the opportunity costs of land rise because of rising productivity in agriculture.

The marginal cost curves differ across models for a number of reasons, including the input datasets (e.g., underlying estimates of the opportunity costs of land), modeling methodologies and assumptions, and ecological parameters (e.g., carbon per ha). GTM has lower land opportunity costs and higher carbon densities per ha than the other two models, and consequently model simulations using GTM generally result in the lowest marginal cost estimates (the largest emission reduction per dollar spent; see Figs. 1*A*, 2*A*, and 3*A*). GCOMAP has the highest global estimates of marginal costs in 2010, but by 2020 and 2030, DIMA projects the highest global estimates of marginal costs. The marginal costs in DIMA become substantially more expensive over time.

As expected, the marginal costs of emission reductions will vary by region (24). The three models suggest unanimously that the lowest-cost region is Africa, followed by Central and South America and Southeast Asia. Over 2005–2030, the models project that Africa could provide 0.9–1.5 Gt $CO_2 \cdot yr^{-1}$ for \$20 t^{-1} CO_2, whereas Latin America could provide 0.8–1.7 Gt $CO_2 \cdot yr^{-1}$, and Southeast Asia could provide 0.1–1.1 Gt $CO_2 \cdot yr^{-1}$. At \$100 t^{-1} CO_2, the projections rise to 1.4–1.7 Gt $CO_2 \cdot yr^{-1}$ for Africa, 1.1–1.9 Gt $CO_2 \cdot yr^{-1}$ for Latin America, and 0.3–1.1 Gt $CO_2 \cdot yr^{-1}$ for Southeast Asia.

Costs to Reduce Deforestation by 10% and 50%

Current AD policy proposals focus on compensating reductions in deforestation vis-à-vis predefined national baselines. Countries would estimate their projected baseline deforestation rates for a given period (using methods not yet determined), and then agree to develop policies at the national level to reduce the rates of change. Presumably, with compensated reductions, they would then be paid *ex post* for the reductions they achieve. How much would it cost to achieve 10% and 50% reduction levels between 2005 and 2030? The three models can conveniently link deforestation rates to specific carbon and land rental payments (Table 3).

Our results indicate that a 10% reduction in deforestation rates over the time period would cost \$2–5 t^{-1} CO_2, and a 50% reduction in deforestation rates would cost \$10–21 t^{-1} CO_2. Payment levels in the 10–50% range could generate substantial

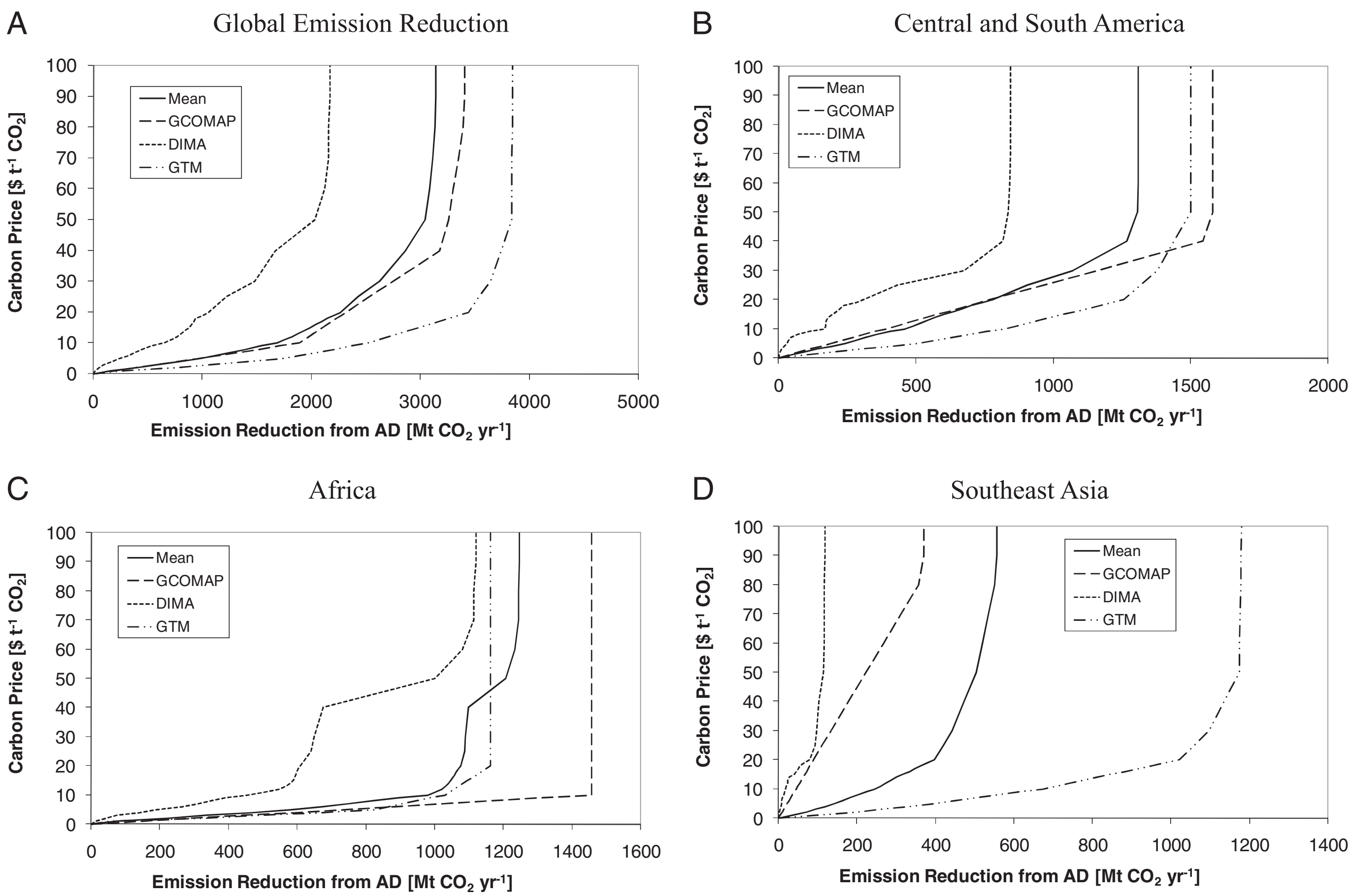

Fig. 3. Marginal costs in 2030 of emissions reductions with AD activities in three regions with predictions of the three models. (*A*) Global emission reduction. (*B*) Central and South America. (*C*) Africa. (*D*) Southeast Asia.

financial flows to landowners who reduce deforestation. Given the carbon intensities described above, carbon prices of \$2 t^{-1} CO_2 could translate into carbon rental values of \$20-\$35 $ha^{-1}{\cdot}yr^{-1}$ for standing forests, whereas carbon prices of \$10 t^{-1} CO_2 would trigger land rental values of \$85-\$252 $ha^{-1}{\cdot}yr^{-1}$. Agricultural rents at the margin of infrastructural improvements (e.g., along new roads in newly accessed regions), where most deforestation occurs, are quite often lower than these estimates, suggesting that in many cases carbon payments could provide powerful economic incentives for reducing deforestation.

Present-value techniques are used to calculate the total costs of reducing deforestation by 10% and 50%. The annual costs of reducing deforestation between 2005 and 2030 are first calculated by multiplying the annual reductions in emissions by the carbon price. The present value of this stream of costs is then calculated, followed by the annual equivalent amount. For internal consistency, individual modelers used their own interest rates to calculate these costs. In the three models, reducing deforestation by 10% globally between 2005 and 2030 could provide 0.3–0.6 Gt $CO_2{\cdot}yr^{-1}$ in emission reductions globally, with annual equivalent costs of \$0.4 billion to \$1.7 billion yr^{-1}. Correspondingly, halving global forest loss could reduce emissions by 1.5–2.7 Gt $CO_2{\cdot}yr^{-1}$, triggering annual equivalent costs of \$17.2 billion to \$28.0 billion yr^{-1}.

Costs of these land-use actions compare favorably to other options for abating carbon emissions. A recent assessment, using three well known energy models, suggested that meeting a 550 parts per million stabilization target would require society to reduce CO_2 emissions by ≈3.5 Gt $CO_2{\cdot}yr^{-1}$ between 2010 and 2030, and would cost \$9 t^{-1} CO_2 (25). None of the models used in that study considered AD, but our estimates indicate that \$9 t^{-1} CO_2 could reduce deforestation by 10–50% over the next 30 years and provide an emission reduction of 0.8–2.5 Gt $CO_2{\cdot}yr^{-1}$. AD could thus provide substantial additional emission reduc-

Table 3. Carbon price in \$ t^{-1} CO_2 necessary to generate a 10% and 50% reduction in deforestation in 2030

	10% reduction, \$			50% reduction, \$		
Area	GCOMAP	DIMA	GTM	GCOMAP	DIMA	GTM
Central and South America	3.98	8.03	1.48	19.86	24.48	9.70
Africa	1.04	3.50	1.63	5.20	12.30	9.60
Southeast Asia	8.42	8.73	1.24	38.15	19.56	8.31
Globe	3.50	4.62	1.41	16.90	20.57	9.27

tions at costs levels consistent with the energy models, while providing numerous ecological and environmental benefits in addition to greenhouse gas mitigation.

These results imply that reducing emissions from AD is a relatively low-cost option, although those costs in absolute terms are not tiny. Reducing deforestation by ≈10% over the next 25 years would cost \$1.2 billion yr^{-1}. This estimate is lower than current global forestry investments of ≈\$18 billion yr^{-1} (26), but note that most current forestry investments are private and occur domestically in developed countries. Public funding of forestry through official development assistance (ODA) and official aid (OA) has averaged \$564 million during 1996–2004 (27). Although they have not to date been widely used for forest and land use projects, carbon markets may provide additional opportunities for AD funding in the future. The market for certified emissions reductions currently trades \$2.7 billion yr^{-1} (28), but it continues to increase. Resources available for AD will grow if a climate policy framework for post-2012 is developed with explicit reference to AD activities (29).

Additional Factors Influencing Costs

Examples of existing programs to protect forests in Costa Rica, Mexico, and India (11, 30) indicate that forest conservation is possible with well designed tools and well funded programs. Conversely, cases exist where few environmental services are paid for, and land users receive minimal payments with minimal incentive effects (31). Experiences with payments for environmental services are thus incipient. Some factors discussed in the above references, but not counted in our estimates, could increase total costs.

First, setting up, implementing, and verifying projects to reduce deforestation could have additional costs beyond the carbon itself. For Clean Development Mechanism (CDM) type AD, afforestation, and other offsets projects, these "transactions" costs have been estimated to range from \$0.03 t^{-1} CO_2 for large projects to \$4.05 t^{-1} CO_2 for smaller ones, with a weighted average of \$0.26 t^{-1} CO_2 for all projects (32). Even if AD programs shift from the project-based approach and instead focus on country-level "compensated reductions," verification expenses could be higher yet because all tons of carbon in a country will have to be measured, not just the tons in areas where forest protection activities are undertaken.

Second, accounting for leakage could impose additional costs, given that current estimates of leakage in forestry projects range from 10% to >90% (33, 34). Transactions costs and potential leakage may partly explain why the contribution from afforestation in the CDM has been minimal in the KP. The cap on Annex I use of credits from afforestation is 1% of 1990 emissions, but actual uptake of existing projects suggests that only ≈1% of this 1% will be used for implementation during the first commitment period.

Third, the right type of incentive or policy to change land use will vary from country to country, and experimentation may take many failures before success is achieved. This may be particularly true in regions where there are no legal *a priori* owners of the land threatened by deforestation, and it is difficult to identify which actors are adequate targets for incentive payments (35). Experiences from microfinance schemes and payments for environmental services from forests (36, 37) do provide useful frameworks for how to deliver, but the implementation challenges of this novel tool would probably not be small.

Conclusion

Reducing emissions from deforestation, a major source of CO_2, could potentially be a highly cost-effective option for climate policy. Using three global forestry and land-use models, we calculate that emission reductions from AD activities could provide substantial quantities of carbon at prices suggested by energy models. For carbon prices of \$100 t^{-1} CO_2, emission reductions of 3.1–4.7 Gt $CO_2 \cdot yr^{-1}$ could be obtained through AD activities during 2005–2030. A 10% reduction in deforestation could be accomplished for \$0.4 billion to \$1.7 billion yr^{-1}, providing emission reductions of 0.3–0.6 Gt $CO_2 \cdot yr^{-1}$ during 2005 to 2030 if efficiently implemented. A 50% reduction in deforestation could reduce emissions by 1.5–2.7 Gt $CO_2 \cdot yr^{-1}$ during 2005 to 2030, but it would cost substantially more, \$17.2 billion to \$28.0 billion yr^{-1}. These estimates are based on economic models that do not consider transactions costs and other institutional barriers, which raise costs in practice. However, a 10% reduction in the rate of deforestation could be feasible within the context of financial flows available through the current CDM and ODA/OA assistance. Policymakers need to develop clear incentives for countries to adopt baselines and national targets so that systems can be developed to credit reductions in deforestation, thus paving the way for funding AD activities.

Methods

The three models used in this analysis have been developed separately by three different modeling groups. *SI Appendices 1–3* provide further details on each of the models. Each model calculates a baseline quantity of carbon sequestered in forests over a varying time horizon, which depends on the specific model. This analysis presents results only through 2030. The baseline for each model embeds model-specific assumptions about the future evolution of agricultural land rents, demand for forestry products, technology change, and other economic drivers (see *SI Appendices 1–3*). As a consequence of these economic processes, the models will project deforestation into the future and the resulting emissions of carbon into the atmosphere.

The models are then used to calculate the quantity of carbon in forests under alternative carbon price regimes. Carbon prices used in this analysis range from \$0 t^{-1} CO_2 to \$100 t^{-1} CO_2. These prices are held constant across the entire time horizon for each model. Because carbon has value, less deforestation occurs in the models under the carbon price scenarios. Emission reductions are calculated as the difference between net annual emissions with a positive carbon price and net annual emissions in the baseline between 2005 and 2030. The marginal cost of emission reductions is the carbon price under the different scenarios. For Figs. 1–3, the individual models are used to calculate the reduction in emissions from AD at the specific time periods analyzed (2010, 2020, and 2030).

1. Intergovernmental Panel on Climate Change (2007) *Climate Change: Synthesis Report* (Cambridge Univ Press, Cambridge, UK).
2. Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-Being: Scenarios* (Island Press, Washington, DC).
3. United Nations Food and Agricultural Organization (2006) *Global Forest Resources Assessment 2005: Progress Toward Sustainable Forest Management* (Food and Agriculture Organization of the United Nations, Rome), FAO Forestry Paper 147.
4. Bala G, *et al.* (2007) Combined climate and carbon-cycle effects of large-scale deforestation. *Proc Natl Acad Sci USA* 104:6550–6555.
5. Williams M (2003) *Deforesting the Earth: From Prehistory to Global Crisis* (Univ. of Chicago Press, Chicago).
6. Geist HJ, Lambin EF (2002) Proximate causes and underlying driving forces of tropical deforestation. *BioScience* 52:143–150.
7. Angelsen A, Kaimowitz D (1999) Rethinking the causes of deforestation: Lessons from economic models. *World Bank Res Observer* 14:73–98.
8. Schaeffer R, *et al.* (2005) Underlying causes of deforestation. *Science* 307:1046–1047.
9. Fearnside PM (2006) Tropical deforestation and global warming. *Science* 312(5777):1137.
10. Morton DC, *et al.* (2006) Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *Proc Natl Acad Sci USA* 103:14637–14641.
11. United Nations Framework Convention on Climate Change Secretariat (2006) *Background Paper for the Workshop on Reducing Emissions From Deforestation in Developing Countries, Part II: Policy Approaches and Positive Incentives* (United Nations Framework Convention on Climate Change, Bonn, Germany), Working paper no. 1.
12. Schulze E-D, *et al.* (2003) Climate change: Making deforestation pay under the Kyoto Protocol? *Science* 299:1669.
13. Persson UM, Azar C (2006) Tropical deforestation in a future international climate policy regime: Lessons from the Brazilian Amazon. *Mitigation Adaptation Strategies Global Change* 12:1277–1304.

14. Moutinho P, Santilli M, Schwartzman S, Rodrigues L (2005) Why ignore tropical deforestation? A proposal for including forest conservation in the Kyoto Protocol. *Unasylva* 56:27–30.
15. United Nations Framework Convention on Climate Change Secretariat (2005) *Reducing Emissions from Deforestation in Developing Countries: Approaches to Stimulate Action* (United Nations Framework Convention on Climate Change, Bonn, Germany), FCCC/CP/2005/Misc.1.
16. Soares-Filho BS, *et al.* (2006) Modeling conservation in the Amazon basin. *Nature* 440:520–523.
17. Gullison RE, *et al.* (2007) Tropical forests and climate policy. *Science* 316:985–986.
18. Rokityanskiy D, *et al.*(2007) Geographically explicit global modeling of land-use change, carbon sequestration, and biomass supply. *Technol Forecasting Social Change* 74: 1057–1082.
19. Kindermann GE, Obersteiner M, Rametsteiner E, McCallum I (2006) Predicting the deforestation trend under different carbon prices. *Carbon Balance Management* 1:1–15.
20. Sathaye J, Makundi W, Dale L, Chan P, Andrasko K (2005) *Estimating Global Forestry GHG Mitigation Potential and Costs: A Dynamic Partial Equilibrium Approach* (Lawrence Berkeley National Laboratory, Berkeley, CA), Working Paper LBNL 55743.
21. Sathaye J, Makundi W, Dale L, Chan P, Andrasko K (2006) GHG mitigation potential, costs, and benefits in global forests. *Energy J* 27:127–162.
22. Sohngen B, Mendelsohn R, Sedjo R (1999) Forest management, conservation, and global timber markets. *Am J Agric Econ* 81:1–13.
23. Sohngen B, Mendelsohn R (2003) An optimal control model of forest carbon sequestration. *Am J Agric Econ* 85:448–457.
24. DeFries RS, *et al.* (2002) Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s. *Proc Natl Acad Sci USA* 99:14256–14261.
25. Clarke LE, *et al.* (2007) *Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations* (U.S. Climate Change Science Program, Washington, DC), Synthesis and Assessment Product 2.1a.
26. Tomaselli I (2006) *Brief Study on Funding and Finance for Forestry and Forest-Based Sector: Report to the United Nations Forum on Forests Secretariat* (United Nations, New York).
27. Organization for Economic Cooperation and Development (2005) *Development Co-operation Report 2005: Efforts and policies of the Members of the Development Assistance Committee* (Organization for Economic Cooperation and Development, Paris), Vol 7, Issue 1.
28. Capoor K, Ambrosi P (2006) *State and Trends of the Carbon Market 2006* (World Bank and International Emissions Trading Association, Washington, DC).
29. Viktor DG, House JC, Joy S (2005) A Madisonian approach to climate policy. *Sci Policy Forum* 309:1820–1821.
30. Ravindranath NH, Murali, KS, Malhotra, KC (2000) *Joint Forest Management and Community Forestry in India: An Ecological and Institutional Assessment* (IBH, New Delhi, India).
31. Wunder S, Buid Dung T, Ibarra E (2005) *Payment Is Good, Control Is Better: Why Payment for Environmental Services in Vietnam Have So Far Remained Incipient* (Center for International Forestry Research, Bogor, Indonesia).
32. Antinori C, Sathaye J (2007) *Assessing Transaction Costs of Project-Based Greenhouse Gas Emissions Trading* (Lawrence Berkeley National Laboratory, Berkeley, CA), LBNL Report 57315.
33. Sohngen B, Brown S (2004) Measuring leakage from carbon projects in open economies: A stop timber harvesting project as a case study. *Can J Forest Res* 34:829–839.
34. Murray BC, McCarl BA, Lee H (2004) Estimating leakage from forest carbon sequestration programs. *Land Econ* 80:109–124.
35. Wunder S (2007) The efficiency of payments for environmental services in tropical conservation. *Conserv Biol* 21:48–58.
36. Mayrand K, Paquin M (2004) *Payments for Environmental Services: A Survey and Assessment of Current Schemes* (Unisféra International Center For the Commission for Environmental Cooperation of North America, Montreal).
37. Pagiola S, Arcenas A, Platais G (2005) Can payments for environmental services help reduce poverty? An exploration of the issues and the evidence to date from Latin America. *World Dev* 33:237–253.

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An assessment of monitoring requirements and costs of 'Reduced Emissions from Deforestation and Degradation'

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Abstract

Background: Negotiations on a future climate policy framework addressing Reduced Emissions from Deforestation and Degradation (REDD) are ongoing. Regardless of how such a framework will be designed, many technical solutions of estimating forest cover and forest carbon stock change exist to support policy in monitoring and accounting. These technologies typically combine remotely sensed data with ground-based inventories. In this article we assess the costs of monitoring REDD based on available technologies and requirements associated with key elements of REDD policy.

Results: We find that the design of a REDD policy framework (and specifically its rules) can have a significant impact on monitoring costs. Costs may vary from 0.5 to 550 US$ per square kilometre depending on the required precision of carbon stock and area change detection. Moreover, they follow economies of scale, i.e. single country or project solutions will face relatively higher monitoring costs.

Conclusion: Although monitoring costs are relatively small compared to other cost items within a REDD system, they should be shared not only among countries but also among sectors, because an integrated monitoring system would have multiple benefits for non-REDD management. Overcoming initialization costs and unequal access to monitoring technologies is crucial for implementation of an integrated monitoring system, and demands for international cooperation.

Background

Globally, by far, the biggest greenhouse gas mitigation potential in forestry is reducing emissions from deforestation. The negotiations on a future REDD (Reduced Emissions from Deforestation and Degradation) policy framework are ongoing and many options exist for its implementation [1]. REDD activities will need to be based on scientifically robust estimates of emissions if they are to be effective. This requires methodologies for Monitoring, Reporting and Verification (MRV) of emissions that follow the United Nations Framework Convention on Climate Change (UNFCCC) principles of transparency, consistency, comparability, completeness, and accuracy [2]. Practicable approaches for monitoring changes in forest and vegetation carbon for REDD will involve the interpretation of remotely sensed imagery (including both airborne and satellite imagery). For many potential REDD applications, remote sensing technologies for REDD are often no longer technically constrained, as has been shown by several studies for many regions [3-5]. A variety of methods can be applied depending on national capabilities, available resources, deforestation patterns and forest characteristics. Porrùra et al. [6] as well as Achard et al. [5] identified the following key requirements for implementing national systems for monitoring REDD: international commitment of resources to increase capacity, coordination of observations, standardized consensus protocols, and access to data at the appropriate resolution at low costs.

A key element of the REDD discussion are monitoring costs. Their estimation and extent will have an impact on the success of REDD mechanisms. Monitoring costs, however, will depend also on the scope and implementation of REDD mechanisms. Elements that will have an influence on the costs include the payment scheme for REDD, whether it is market or non-market based or a combination of such. The scope of the system, either national or sub-national, will have an impact on the costs as well as the type and level of verifications that will be applied. In this article we identify key elements of REDD policy, evaluate requirements for monitoring efforts and assess their costs.

Results

Evaluation of monitoring requirements associated with key elements of REDD policies

REDD policies and REDD monitoring systems will coevolve. A REDD monitoring system needs to be designed to serve known current and future REDD policy requirements conditional on technical capabilities and costs. Likewise, future REDD policy designs will need to be based on comprehensive, international consistent and accurate spatially explicit data on global forest change and carbon stocks, emissions and trends. Herold and Johns, [7] define a REDD monitoring framework with a set of "minimum common characteristics" to provide a starting point for actors to engage in implementation activities, and to support REDD early actions and readiness mechanisms for building national REDD monitoring systems. Here we define a list of elements extracted from the recently proposed REDD policy approaches that are translated into monitoring requirements.

Under the UNFCCC and Kyoto Protocol, no climate policies exist to reduce emissions from deforestation or forest degradation in developing countries. In December 2005, COP-11 established a two-year process to review relevant scientific, technical, and methodological issues and to consider possible policy approaches and positive incentives for reducing emissions from deforestation in developing countries [8,9]. Recent research suggests a broad range of possible approaches to effectively reduce emissions from tropical deforestation and forest degradation, e.g.; [10-12].

Most approaches suggest voluntary participation and require an assessment of historic and future deforestation rates based on detectable change in forest area using remote sensing imagery. The use of positive incentives as a source of finance for activities and policies is the ultimate basis of all proposals. The scope and design of the REDD approach (to be finally adopted) has implications for monitoring and verification efforts. From the proposals analyzed in this study we identified several aspects relevant for monitoring (in general) and for costs of remote sensing, change detection and verification (in particular) (see Table 1).

Different monitoring options are available to detect change of forest cover and of carbon stocks within forests (see Section "Assessment of monitoring technologies and costs" below). It has to be considered that the decision of which monitoring system will be applied in the final REDD system will not depend on availability of technologies alone. Policy makers will base their decision on the REDD design considering other factors including: definitions, scale and scope of activities, financing mechanisms, trading of credits and their own country context. In the following text we provide an outline of the role of monitoring within a REDD system.

Definition of forests, deforestation and degradation

According to the Food and Agricultural Organization (FAO), the definition of deforestation refers to a change in land cover with depletion of tree crown cover to less than 10 percent [13]. The UNFCCC defines deforestation as "the direct human-induced conversion of forest land to non-forest land" (paragraph 1(b) of the Annex to Decision 16/CMP.1).

Changes within the forest class (e.g. from closed to open forest) which negatively affect the stand or site and, in particular, lower the production capacity, are termed forest degradation.

The Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG LULUCF) of the Intergovernmental Panel on Climate Change (IPCC) as well as the 2006 guidelines for Agriculture, Forestry and Other Land Uses (AFOLU) include definitions that might be used as a basis for definitions in a potential REDD mechanism. The options for definitions of forests and deforestation within future policy frameworks might range from the applica-

Table 1: Main elements of different proposals for approaches to reduced deforestation and degradation (based on [58,59]).

Element	Examples of variation in implementation
Definition of forests, deforestation and degradation	National definitions Technically detailed versus general (e.g. three classes: forest, degraded forest, non-forest as proposed by Joint Research Centre) Marrakech accords (UNFCCC 2002): 0.05–1 ha minimum area, 10–30% tree canopy cover and a potential of 2–5 m tree height; used by Annex I country Kyoto reporting and CDM projects Others see Mollicone et al. [16] (intact forest, non-intact forest, non-forest) Deforestation versus deforestation **and** degradation
Scale Minimum Mapping Unit Target area	National versus projects National, sectoral Sub-national Projects Definition of MMU
Reference level, baseline Data for baseline Baseline development	National historical averages with a correction for countries which have already significantly reduced deforestation; compared to reference (e.g. 1990 or 2000) Global average deforestation rate, countries with less than half the global average will be credited for not increasing deforestation, geographical Sophisticated prognostic **model** of land competition
Carbon model	Simple, national average carbon stock versus sophisticated assessment Inventory versus IPCC default values Simple, national average carbon stock for both intact and non-intact (degraded) forest Detailed carbon maps based on RS
Financing mechanism and trading	Instruments: Market-based Tax Incentives Units created for trade: Certified emission reductions (CERs) in CDM projects: Short-term credits (tCERs) Long-term credits (lCERs) Voluntary carbon market: Not entire forest area accounted for Only specified amount banked as buffer.

tion of existing national definitions to globally harmonized definitions such as the FAO. They might be based on technically detailed descriptions like those prescribed by the Marrakech Accords (UNFCCC 2002: 0.05–1 ha minimum area, 10–30% tree canopy cover and a potential of 2–5 m tree height) and used by Annex I countries for Kyoto reporting and CDM projects. Existing inventories can provide such technical features of forests in developed countries.

Technical requirements and associated costs between a RED (without degradation) and a REDD (including degradation) monitoring system would turn out to be starkly different. Measuring forest degradation through remote sensing is technically more challenging. In the transition from intact to degraded forest the canopy may still be closed (or closed again), whilst the carbon stocks may be reduced by up to 75% [14]. In addition, it may take place far from access features such as roads and rivers where it is even more difficult to detect. Compared to deforestation, degradation has therefore not been quantified in most countries in the past. Recently, Asner et al. [15] showed for an area of over two million square kilometres in the Brazilian Amazon that at least 76% of all selective harvest practices resulted in high levels of canopy damage and significant amounts of biomass removal.

A more general approach discussed for tropical forests and proposed from a monitoring perspective by the Joint Research Centre [16] forms three classes: forest, degraded forest, non-forest. Regardless of how such a classification will look like in detail (number of classes, parameters included in definition of strata, etc.), stratification of the forest landscape to be monitored is key to lower costs and still maintain a high level of precision and accuracy [17].

Recently, the UNFCCC negotiation enhanced the REDD discussion with the inclusion of sustainable forest management and the conservation and enhancement of forest carbon stocks [18]. Monitoring requirements and costs for "REDD plus" could differ from those that focus only on the original REDD notion. However, methodologically similar technologies are involved. The definitions would have to include relevant activities such as afforestation reforestation, sustainable forest management etc.

Scale and scope

At the current stage it remains unclear if the REDD mechanism will be applied at the national level or sub-national level, or a combination of both. Likewise, it is unclear whether monitoring will in the end be done on the project, country or even global scale. Following a project approach (compared to national level measures like inventories), simplifies quantification and monitoring efforts because of the clearly defined boundaries for project activities, the relative ease of stratification of the project area, and the choice of carbon pools to measure [6]. At the national level, costs will differ significantly between countries as costs for monitoring activities are related to the size of the country, i.e. the area to be monitored [19].

The Minimum Mapping Unit (MMU) required for effective monitoring directly influences the costs of monitoring. Remote sensing data analysis becomes more difficult and more expensive with smaller MMUs, i.e. more detailed MMUs increase mapping efforts and usually decrease change mapping accuracy [7]. For example, using optical remote sensing, the use of 30 m resolution imagery results in a MMU of ca. 0.1 ha, while data with 5 m resolution allows MMUs of 0.01 ha and smaller (RapidEye pers. comm.).

Emission displacement

GHG emissions displacement might occur when interventions to reduce emissions in one geographical area (subnational or national) cause an increase in emissions in another area through the relocation of activities. Monitoring of REDD also needs to address this leakage of emissions which will have direct implications for monitoring costs.

Wall-to-wall coverage (i.e. analysis of satellite data that covers the full spatial extent of the forested area), with high resolution satellite imagery or even with airborne imagery will provide a high level of certainty to estimate land-use change [17]. A globally consistent forest carbon observatory with wall-to-wall mapping would partly address the problem of leakage that is often associated with project level approaches. This analysis is ideal, but often not practical due to large areas and constraints on resources for analysis. An alternative approach to wall-to-wall coverage is sampling. Several approaches have been successfully applied to sample within the total forest area to reduce both costs and the time for analysis [17].

However, to be effective, an assessment of displacement of REDD would require a "land based" reporting approach. Clearly, a global forest carbon observatory would probably also yield the lowest cost solution per MRV-REDD unit by reaping the most of economies of scale. Economies of scope relate to the fact that in a "system of systems" approach, such as GEOSS (Global Earth Observation System of Systems), one observing system creates benefits to another. For example, an Earth Observation (EO) satellite system dedicated to yield and acreage estimation in agriculture could at the same time be used for deforestation monitoring. Thus, the cost per unit carbon from REDD will be decreased by its complementary use for agricultural monitoring.

Additionality and choice of reference level

REDD policies have to address the difficulty in determining additionality compared to a baseline. Historic baselines use national historical averages as reference and compare them to current rates. However, reliable estimates of historical carbon emissions from deforestation and degradation are de facto not available. Considerable (re-)analysis of recently opened remote sensing archives would be necessary. Similarly, global average deforestation rates are discussed that would require less historic deforestation data at the national level. Models for baseline estimations range from relatively simple extrapolations of past trends in land use to more complex extrapolations of past trends using spatially explicit models of land-use change driven by biophysical and socioeconomic factors [20]. Sophisticated prognostic models of land competition that could be employed to provide forward-looking baselines of deforestation pressures (Obersteiner, M. et al.: Avoiding REDD hot air – an IIASA proposal for generating standardized and globally consistent national reference scenarios that maximize sustainability, submitted) require a lot of data streams to be assimilated in these models. Such data streams range from socio-economic census data, forest ownership and governance data to detailed climatic and land use information derived from EO. The overall costing for the latter baseline establishment scenario is more complex than the observing system. It not only covers the physical monitoring of the forest per se, but the entire planning, monitoring and evaluation phase of REDD implementation and other associated policies. Sensitivity analysis within these more complex economic land use models is required to deliver robust cost estimates of avoided deforestation. Moreover, such models can be used to determine the level of accuracy at which the data has to be collected and so determine the cost-benefit relationship of incremental costs versus the incremental benefits of better EO and more detailed socio-economic data [21].

Carbon model

There is a great diversity of methods for estimating carbon stocks in forests. Therefore, it is extremely important for the planning of forest carbon observation systems to agree internationally on common methods and standards. Three approaches (tiers) for estimating carbon are proposed by the IPCC LULUCF [19,22]. Tier 1 is based on default assumptions and default values for carbon stocks e.g. for different forest types. In tier 2, country-specific carbon stocks are applied to activity data, disaggregated to appropriate scales. In tier 3, countries use advanced estimation approaches that may involve complex models and highly disaggregated data including detailed maps based on remote sensing as well in-situ measurements. Estimates of carbon provided by the GPG tier 3 approach yield the lowest uncertainties, but involve the highest MRV costs.

The GOFC-GOLD sourcebook reviews in detail the question of which tier should be used. The choice is relevant not only for costs but also for the level of total uncertainty. The error in applying a relatively coarse IPCC Tier 1 approach (as compared to carbon stocks estimated from ground plot measurements from six sites around the world) can range between an overestimation of 33% to an underestimation of 44% [17]. The sourcebook further highlights that despite a constant low uncertainty of 5% for the area change component, the uncertainty of the total final estimate of emissions is governed by the higher uncertainty in the carbon stock data. Therefore, it can be said that if uncertainty cannot be reduced to equal levels for the emission factor, "investment in an unbalanced half is money poorly spent" (page 55 in [17]).

It is currently still unclear, which level of minimum precision and accuracy is required under which REDD implementation scenario. Moreover, no decision is made on the system boundaries, i.e. which carbon pools are going to be included in REDD. While including soil carbon pools will increase uncertainty and costs, an integrated forest sector view including harvested wood products might actually decrease relative uncertainty of carbon stock change estimates (compared to total carbon stocks) [23] due to system integration. Thus, also within a REDD framework, even pools with high uncertainty should rather be included by applying conservative default values [2].

Implementation mechanisms

REDD aims to encourage permanent forest management to ensure that carbon emissions are not occurring. Permanence is therefore the core element of the whole REDD approach and points to the requirement of temporal consistency of monitoring. At the moment, different financing options are discussed including fund based and market based approaches [1]. While a non market based international REDD fund might not have to rely for its operations on detailed carbon accounting (it could instead, in a first phase, focus on capacity building in the forest sector through technical cooperation programs or fund agricultural intensification programs), a market based approach will require detailed measurement of carbon emissions avoided from REDD activities. On the level of (sub-)national REDD programs, the implementation of a deforestation tax system will require different observational capabilities as a REDD carbon trading system or a REDD subsidy program. Furthermore, the observational requirements will vary, as within a country land tenure is not always clearly defined and secure.

Trading

In a market based approach, carbon credits are traded on the carbon market and paid by private or sovereign clients. Different trading mechanisms have been discussed including different types of credits (e.g. temporary versus permanent credits). Under the CDM projects relating to afforestation and reforestation (A/R), a system of temporary credits has been implemented which differentiates between short-term credits (tCERs) and long-term credits (lCERs) [24].

Short-term credits are given for existing carbon stocks at the time of verification, which expire after 5 years. Verification takes place again every 5 years until the end of the project period, taking changes in carbon stocks into account by adjusting the number of tCERs issued every 5 years [24]. To determine the changes in carbon stocks every 5 years, frequent monitoring is required. In case of forest loss the carbon credit buyer is liable to cover the lost credits; therefore this option is not very attractive to the credit buyer because the entire liability and risk lies with him.

A different approach to issue permanent carbon credits is currently applied on the voluntary carbon market by VCS (Voluntary Carbon Standard) and Carbon Fix standards [25]. This approach is based on the concept that not all forest area or carbon credits are accounted for, but a specified amount of forest area or carbon credits are placed in a buffer. In case forest loss is identified, the buffer is reduced. If no forest is lost over a specified time period the buffered amount can be retrieved, providing an additional incentive to maintain the forest. The size of the buffer is determined through a risk assessment. In this approach, monitoring is important to identify forest loss in a timely manner thus triggering the reduction of the buffer. The incentive system can also be closely linked to the monitoring system as a tiered approach similar to the one applied in IPCC LULUCF and AFOLU. In this case, tiers represent increasing levels of data requirements and with increased tiers the buffer can be reduced. The increased costs for monitoring would be covered through the additional amount of credits received. Different to the tCERs, the carbon credits in the voluntary market are permanent credits and the liability is with the carbon credit seller, covered through the buffer. From this perspective it is more attractive to the carbon market.

Each of these elements discussed above offers various options for implementation. An international agreement might also leave the final implementation to the member states, prescribing only the range within which countries have to choose their definition (i.e. the forest definition in the Kyoto Protocol implementation as defined in the Marrakech Accords).

The more flexibility such an agreement leaves to each country for implementation, the more options a country has for a cost efficient and locally adapted design of its monitoring systems. Thus, it appears that a clear choice for the right monitoring system for the ultimate REDD carbon trading is not yet possible. However, the exchange rate between a REDD unit and an Assigned Amount Unit will surely also depend on the level of measurement uncertainty of individual REDD units. The less MRV a REDD unit will appear, the more it will be discounted.

Assessment of monitoring technologies and costs

Remote sensing will be an essential method to establish baselines and monitor progress in reducing emissions from deforestation and there will be considerable need to build capacity in this regard in many non-Annex I countries [26,27]. The following section will briefly describe the technologies, with a special focus on their costs.

Forest area and carbon stock change detection

The assessment of emissions from deforestation and degradation requires data on both change in forest cover and estimates of carbon stock changes associated with transition between land use types [8]. It is an estimation process that includes measured data and the application of models at many levels, with different uncertainties. The IPCC has compiled methods and good practice guidance [22] to move from two-dimensional (forest area) to three-dimensional (carbon stocks) evaluation of changes. It is worth mentioning here, that the IPCC suggests the use of remote sensing technologies only to assess forest area changes, while there are no suggestions for the use for direct biomass estimates. The methodology needs to be consistent at repeated intervals, and results need verification with ground-based or very high resolution remote observations [28]. As Goetz et al. [29] concluded from a review of different approaches to estimate above ground biomass, mapping attempts without satellite imagery are often insufficient while direct remote sensing approaches provided more coherent maps of forest biomass compared to other approaches.

Satellite sensors can be generally grouped into optical and radar systems. Both systems collect data routinely and at least at moderate resolution, data are often freely available (at the global scale). The quality of global products derived from those sensors depends upon many factors (e.g cloud cover, solar angle, wavelength, etc.), the need for time series, and the availability of ancillary data for validation. A wide spectrum of bands and radiometric resolution offer high information content. However, there is still a limited ability to develop accurate biomass estimation models for tropical forests based on remotely sensed optical data [29]. Early saturation of the signal is the limiting factor in optical systems, along with persistent cloud cover in many of the regions of high biomass over the globe, in particular in the tropical zone. Global optical sensors often process composite images using data covering two to four weeks to avoid cloud and cloud shadow. Medium and high-resolution sensors usually have more problems to obtain cloud free data. In addition, optical data are sensitive to phenological and surface properties of vegetation.

Random errors in the methods applying optical remote sensing for deforestation detection typically range from a few per cent up to 20%, depending on sampling frequency, sample size and deforestation rates, e.g., [30]. Systematic errors occur due to interpretation of satellite images or inappropriate forest classification algorithms and are assessable through ground observations or by analyzing very high-resolution aircraft or satellite data [5] This type of error might be larger in a wall-to-wall approach because a larger area is included. With medium-resolution imagery, systematic errors of 5–20% are achievable for monitoring changes in forest cover when using only two classes (forest and non-forest; [30,31]). The application of satellite or airborne high resolution optical sensors reduces the time and cost of collecting forest inventory data and results in high accuracy. These flights can be undertaken when there is no cloud cover. Such datasets are excellent ground verification for a deforestation baseline but are expensive and technically demanding [3]. The high resolution yields relatively small areas of coverage (e.g.10,000 ha).

Technologies based on Synthetic Aperture Radar (SAR) backscatter depend on the number of scattering elements seen by the radar wave, as well as on their geometric and dielectric properties. These features are directly related to parameters expressing forest density such as the forest growing stock volume [32]. A method for estimating forest biomass maps relates observed backscattering or interferometric coherence data to ground measurements of forest biomass. Improvements in the estimation can be achieved by combining different polarizations and by combining different frequencies. Compared to optical sensors in terms of biomass detection, SAR sensors have the advantage of being able to penetrate clouds and to a limited extent, the forest canopy (dependent upon wavelength). For young and sparse forests the technique achieves high accuracies. The method is less accurate in complex canopies of mature forests because the signal saturates. This can however be compensated somewhat with increasing wavelength and repeated observations. Typically the saturation effect is observed for satellite based SAR systems with low frequencies (P-band) at ~150 tons/ha, and higher frequencies (L-band) at ~100 tons/ha [33,34]. Additionally, in mountainous terrain, the error increases [3].

There are a number of new and innovative technologies which have recently approached operational feasibility, such as light detection and ranging (LiDAR, [28]). LiDAR techniques involve large amounts of data handling and require extensive field data for calibration, which create both a financial and time burden. Airplane-mounted sensors accurately estimate the full spatial variability of forest carbon stocks. This offers a large potential for satellite-based systems to estimate global forest carbon stocks. Future satellite LiDAR systems cannot feasibly "image" from space, but will augment global observations of canopy profiles to more accurately derive biomass at the plot scale. LiDAR systems with large footprints (> 5 m) produce estimates of mean tree height, canopy cover, or canopy density for an area. Regression models constructed using ground measurements, LiDAR data, and ancillary data may then be used to predict accurate estimates of forest carbon stocks [35-37]. Although predictions of diameter and volume may have considerable uncertainty for individual trees, estimates at stand- or plot-level may still be acceptably precise [35].

A 'hierarchical nested approach' combines high and coarse resolution optical, SAR, and/or LiDAR data [38-41]. Coarse resolution optical or SAR is used to identify areas of rapid land use change that then become the focus of further study with higher resolution imagery. This process of sub-sampling can be automated or based on knowledge of deforestation fronts by experts who identify areas of deforestation pressure [42]. A probability-based sampling approach was applied by Hansen et al. [4] that employs MODIS data to identify areas of likely forest cover loss and to stratify probability of forest clearing. Random samples in the strata were interpreted for forest cover and forest clearing by using high-spatial-resolution Landsat imagery. Other data such as maps of infrastructure, population changes in rural areas and maps of policy programs can be used to identify such hot spot areas where a more detailed analysis is required [17]. With the help of such an approach, monitoring systems at national levels in developing countries can also benefit from pan-tropical and regional observations, mainly by identifying hot spots of change and prioritizing areas for monitoring at finer spatial scales [5]. However, finding an adequate sampling method that is dense enough and well designed to capture deforestation events (that are not randomly distributed in space but e.g. along roads, etc.) remains a challenge and will depend on accuracy and precision requirements from the policy process.

Traditional (national) forest inventories (NFI) provide data of the growing stock timber volume per unit area by tree diameter or age classes and species composition. To estimate changes in growing stocks, repeated measurements at permanent sample plots are carried out. There are a few developing countries like India and China that are conducting a national forest inventory on a regular basis [17]. The biomass stock of forest trees in NFIs is usually calculated by using Biomass Expansion Factors (BEFs) that convert timber volumes to dry weight (density factor) and dry weight to whole tree biomass (expansion factor). BEFs are either constant or a function of stand development and exist for many species of temperate forest, e.g. [43,44]. However, there are only a few biomass functions for tropical species [45,46]. Additional destructive biomass measurements would be needed to develop biomass expansion factors and estimate carbon densities. Including such labor intensive activities in an estimation of monitoring costs would of course mean a cost shift at the project level. However, such costs will diminish over time and their reduction can also be achieved by collaboration and scientific exchange.

In many developing countries there are obvious limitations in the availability of appropriate reference data especially for the period 1990–2000. If no robust reference data are available, at a minimum, a consistency assessment should allow some estimation of the forest change quality, i.e. reinterpretation of small samples in an independent manner by regional experts. When completeness or accuracy of estimates cannot be achieved, high uncertainties in input data can be overcome by applying the conservativeness principle [2], which guarantees that the reduction of emissions is not overestimated, or at least the risk of overestimation is minimized. In the context of total emissions from deforestation and degradation, Schlamadinger et al. [47] proposed a corridor to reflect the uncertainty of future emissions. This corridor could be derived using historical emissions, emission trends, and trends in underlying causes.

Costs of REDD monitoring technologies

Table 2 lists costs for REDD monitoring including remote sensing technologies and inventories. In general, the costs for monitoring will depend on the requirements within REDD which is mainly determined by the accuracy level. The accuracy level will determine the monitoring technology applied, each requiring different ways of data acquisition, processing, training and capacity building. The factors that influence the price of the data acquisition are the amount of ground-based and EO data needed.

Financial resources for remote sensing assessments of deforestation and degradation are required to acquire suitable satellite data, for processing hardware and software, training and capacity building, data processing and analysis, field work and travel, and for accuracy assessment. The costs for EO are determined by the data quality, resolution, cloud cover, order size, imaging window, and provider. Data processing costs occur for: hardware, software and data analysis. Overall costs depend on factors like existing capabilities and capacities and the comprehensiveness of the monitoring systems. However the costs for data analysis requires special REDD adaptations that depend on the degree of automated processes, effort, and accuracy. Costs that occur in acquiring ground-based data are for field work and travel. Whichever REDD system is applied, it is likely that training and capacity building will be needed in all areas which are part of a monitoring process and there will be costs associated with it.

As stated above, the costs of monitoring REDD are a function of the desired level of precision – which may vary by the size of the project, terrain and heterogeneity of the landscape, location of areas and degree of coherence, and natural variation of carbon pools under observation [6], and also by the required standards of the adopted REDD scheme. Where technical capabilities and cost constraints prevent automated digital analysis, pure manual interpretation of aerial photographs or satellite images is an appropriate monitoring method. The need for reproducible and verifiable results can be met through multiple interpreters and well-designed procedures. For countries with sophisticated data acquisition and analysis, more automated analysis with computer algorithms reduces the time required for monitoring and strengthens the efficiency of the monitoring system in the long term [17].

A transparent form of validation could be achieved by publishing interpreted maps on the internet, or even by allowing public validation of land cover interpretation and land cover change (e.g. http://www.geo-wiki.org[48]).

Building on and enhancing traditional and local level forest governance capacities and establishing community-based forest management systems can be an essential step to efficiently prevent and/or monitor deforestation and degradation [49]. This kind of small-scale forest monitoring is cost-effective, and should bring many more benefits to local communities than other large scale measures, thus contributing more strongly to sustainable development [50]. Research projects reviewed by Skutsch et al. [50] showed that carbon measurement and monitoring methods, which were carried out by community members using hand-held computers with GIS capability and GPS, could accurately map forest resource and carbon stocks at relatively low transaction costs. An efficient policy framework for more community-based management will necessarily involve multi-level governance and involve international, national and local level bodies in developed and developing countries [49].

Discussion

Remote sensing has been identified as a key technology to successfully implement and monitor a future REDD mechanism [7]. As described above, technological options are manifold. They range from the analysis of coarse resolution data from optical sensors and the application of average values to sophisticated methods of LiDAR and SAR scanning paired with detailed models. All involve different costs and requirements and also yield different accuracies. Finding the optimal technological pathway is crucial for a successful implementation of REDD. The design of a future REDD mechanism has direct implications for the number of monitoring options and also at what costs they can be implemented. But how do monitoring costs relate to other costs of REDD policy implementation and compliance?

Monitoring costs compared to other costs

Stern [51] identified three types of costs arising from the reduction of deforestation, which are i) opportunity costs previous to the preservation of forests, ii) costs of administration and implementing effective action, and iii) costs of managing the transition. For the purpose of this analysis we differentiate between readiness costs, opportunity costs and implementation costs apart from monitoring costs, the focus of this paper.

Readiness costs

It is clear at this stage that an important cost component is related to making the participating countries ready for

Table 2: Present acquisition and analysis costs* of monitoring services of various technologies in US$.

Satellite and sensor	Resolution and coverage or project area	Costs for data acquisition	Cost for analysis	Total monitoring costs	Source
Optical, medium resolution sensors					
Landsat-5, TM	30 m, 180 × 180 km	0.02 US$/km^2 – free	Classification 0.12–0.31 US$/km^2 Change detection 0.4–0.6 US$/km^2	0.50–1.21 US$/km^2	SARMAP pers. comm.
Landsat-7, ETM+	30 m, 60 × 180 km	0.06 US$/km^2			
SPOT 4	20 m	0.31 US$/km^2			
Terra ASTER	15 m, 60 × 60 km	0.02 US$/km^2			
CBERS-2, HRCCD	20 m	free in Brazil			
DMC	32 m, 160 × 660 km	0.04 US$/km^2			
IRS-P6-LISS III	23.5 m	0.07 US$/km^2	Human resources and equipment 0.5 US$/km^2	0.57 US$/km^2	[19]
Optical, high resolution sensors					
Quickbird	3 m	25 US$/km^2	Classification 2.2–2.5 US$/km^2 Change detection 4.7–7.9 US$/km^2	7.50 – 35.40 US$/km^2	SARMAP pers. comm.
Ikonos	4 m	25 US$/km^2			
RapidEye	5 m	2.8 US$/km^2			RapidEye pers. comm.
SPOT-5, HRVIR	5–20 m, 60 × 60 km	0.6 US$/km^2			SARMAP pers. comm.
Optical, very high resolution sensors					
Quickbird	0.6 m	16–22 US$/km^2	Classification 100–125 US$/km^2	116–272 US$/km^2	SARMAP pers. comm.
WorldView-1	0.5 m	16–22 US$/km^2	Change detection 160–250 US$/km^2	116–272 US$/km^2	SARMAP pers. comm.
Radar, SAR					
ALOS PALSAR	10–15 m	0.04 US$/km^2	Classification 2.2–2.5 US$/km^2	6.94 – 10.44 US$/km^2	SARMAP pers. comm.
Satellite or shuttle SAR		0.14 US$/km^2	Change detection 4.7–7.9 US$/km^2	7.04 – 10.54 US$/km^2	[60]
Airborne SAR		345 US$/km^2		> 345 US$/km^2	[60]
LiDAR, airborne					
UK, forest monitoring, national average	28,000 km^2			415 US$/km^2	[60]
US, forest inventory at project level	40 km^2			455 US$/km^2	[61]
	400 km^2			100 US$/km^2	[61]
US, project area	180 km^2			388 US$/km^2	[62]
Indonesia, forest inventory at project level	136 km^2	400–550 US$/km^2	160 hours processing time	> 400–550 US$/km^2	RSS GmbH pers. comm.
Ground-based inventories and national/project examples					
US, project example	180 km^2, 1000 sample plots			167 US$/km^2	[62]
UK, ground survey	28,000 km^2			172 US$/km^2	[60]
Bolivia, Noel Kempff Project, inventory	6,340 km^2; 625 sample plots	17 – 0.16 US$/km^2**		55 US$/km^2	[63]
Costa Rica, Private Forestry Project, monitoring	570 km^2			100 US$/km^2	[63]

Table 2: Present acquisition and analysis costs* of monitoring services of various technologies in US$. *(Continued)*

Indian National Forest Inventory and additional biomass assessment	677,088 km^2; ca. 7,000 NFI plots + 1,400 additional plots	< 10 US$/km^2	[19]
National Forest Monitoring and Assessment	Total forest monitoring costs of five examples (Zambia, Honduras, Nicaragua, Bangladesh, Cameroon)	1.2 – 8.2 US$/km^2	[64]
Indonesia, Ulu Masen Project	7,500 km^2		
RS monitoring and management		81 US$/km^2	[63]
Airborne monitoring (ultra light aircraft)		200 US$/km^2	

* Costs for analysis and total costs are indicative costs. They include service design, data processing and mapping, interpretation and analysis. The actual costs would depend on the selected sensor, the fit of sensor data to area to be mapped (which determines how many scenes are needed), the amount of GIS (Geographical Information System) processing, integration and support services required to develop final images and maps and integrate these into asset operational and management systems.
** Variable costs dropped rapidly from a precision level of ± 5 percent to a level of ± 30 percent.

REDD. The vast majority of forest nations participating in REDD will face capacity building costs, i.e. costs for establishing research capacity, technology transfer and legal support. Further costs might include those for land tenure reform and governance reform where these are required to facilitate a REDD financing regime. These so called costs for "readiness" are related to capacity building and policy development to create a framework in which the REDD system can be applied. As these types of costs depend on the national context and do not apply in all cases, they should be regarded as a separate cost type. The Eliasch Review [52] estimates that reforms and capacity building within 40 "forest nations" would cost up to 4 billion US$ over 5 years.

Implementation costs

Implementation costs of projects in a REDD system depend on the final structure of the REDD mechanism, whether it is market or non market based, implemented at the national or sub national level, etc. They comprise a variety of costs which include: monitoring, planning, verification, certification, enforcement, administration, insurance, brokerage and governance. There will also be costs involved in addressing the risk of leakage in the implementation of a REDD program. In certain cases, this cost could be high (e.g. where degraded land is reforested to provide a substitute forest for sustainable logging, [53]).

As it is unclear what structure a future REDD system will have, cost estimates for the implementation are difficult. However experience has been obtained in specific carbon related projects. The literature values from single projects can only be compared if they indicate what cost items are included and what the framing scheme looks like. Implementation costs typically range from 400 to 1500 US$/km^2, e.g. [54,55].

When considering these cases for implementation costs for REDD, it has to be taken into account that only specific elements of a future REDD system in local contexts were part of these cases. It is therefore difficult to use these cases for an estimation of implementation costs of a future REDD system. However, it can be seen that each element of the implementation costs has to be considered separately and maybe even looked at in the national/local context to arrive at meaningful estimates.

Opportunity costs

A key variable for deforestation is how attractive land conversion for individual land owners is, based on the balance between forest value and the value of alternative land-use. Opportunity costs represent the highest alternative land-use of the area under deforestation threat, including net revenue from the conversion itself (e.g. value of extracted timber).

Opportunity costs of REDD have been investigated on a project level. Across Africa, Central America, SE Asia, and South America they amount to 30,000–250,000 US$/km^2 ([55], see Table 3). There are big uncertainties associated with the estimation of opportunity costs that depend on regional prices and current status of areas that are deforestation candidates. Opportunity costs are particularly sensitive to percentage area harvested and timber price. Subsistence agriculture – a significant cause for deforestation in many tropical regions, has much lower opportunity costs than areas under deforestation threat for

Table 3: Opportunity costs of avoided deforestation as presented in UNFCCC report Investment and Financial Flows to Address Climate Change [65,66].

Main/Direct Drivers	Area of deforestation/ degradation [million ha]	Share of total deforested/ degraded area [%]	Opportunity cost of forest conversion [US$/km^2]
Commercial agriculture			
Commercial crops	2.6	20%	224,700
Cattle ranching (large-scale)	1.6	12%	49,800
Subsistence farming			
Small scale agriculture/shifting cultivation	5.5	42%	39,200
Fuel-wood and NTFP* gathering	0.75	6%	26,300
Wood extraction			
Commercial (legal and illegal)	1.8	14%	175,100
Fuel-wood/charcoal (traded)	0.7	5%	12,300
Total	12.9	100%	-

* NTFP are non-timber forest products.

commercial agriculture. It has, however, to be considered that the opportunity costs do not necessarily reflect the risk of deforestation. Although low opportunity costs exist, the risk for deforestation may still be high e.g. illegal logging or subsistence agriculture.

Compared to other cost items, monitoring costs of REDD projects are rather low on a per square kilometre basis. Future monitoring costs are likely to decrease because different sampling intensities will be used building on existing data. Additionally, project implementers will be able to build on previous experience. This is especially true for the more cost intensive monitoring efforts like estimating biomass expansion factors or establishing the first inventory. In particular, opportunity costs rule out expenses that even relatively intensive monitoring would require. As Kindermann et al. [56] estimated through a comparison of global land use models, a 10% reduction in deforestation rates until 2030 would cost about 2,000–25,200 US$/km^2 per year as a rent for carbon stocks in forests, assuming a lower (2 US$/t CO_2) and a higher (10 US$/t CO_2) value for a global carbon price.

Co-benefits of integration

There are two types of integration effects with respect to REDD monitoring. The first integration relates to cost savings due to integration of different observation systems/components. When observations are stratified (i.e. higher accuracy and precision in hot spot areas) and different observation systems are integrated to form an observation portfolio (e.g. optical, SAR, LIDAR and in-situ), monitoring costs per MRV REDD unit are minimized. The other integration effect refers to economies of scope when one observing system can yield multiple benefits. In this paper the costs of monitoring for REDD included only the carbon sector. In fact, monitoring of forests has the potential to benefit the development of the forestry sector in general. Those forests monitored for carbon stocks can more easily be assessed for timber supply, the provision of non-timber forest products or other forest functions. Moreover, an integrated monitoring system could result in optimized general land management, including fire management, implementation of land use policies, etc. From an integrated monitoring perspective the currently ongoing discussion on a REDD plus mechanism, that includes measures to lower emissions from deforestation and degradation, also rewards forest management activities that increase carbon stocks in forests. This would help to increase incentives for integrated forest monitoring with associated benefits for the forestry sector.

Other co-benefits exist in the field of ecosystem services with an improved monitoring system, e.g. biodiversity and ecosystem services can be better measured and identified. For example, specific areas of both high carbon value and high ecosystem values can be identified. Additionally, general cadastral mapping services could be supplied by an integrated monitoring system as co-benefits. Disaster management could also be integrated e.g. the Disaster Management Constellation (DMC, http://www.dmcii.com), which is used for many different applications.

However, as previously acknowledged [57], benefits from such an integration can hardly be assessed in detail although their potential has to be considered when monitoring costs are discussed. A good example supporting the value of data integration is the current lack of driver and pressure data for REDD planning. In particular, data from the agricultural sector such as crop maps, information on agricultural management practices, farm size ownership structure and land tenure, all the way to education and health data are virtually impossible to compile from existing statistics. This fact points to yet another dimension of

REDD monitoring, which goes far beyond forest carbon accounting. For implementation planning and subsequent monitoring and evaluation of REDD policies and activities, such data will be indispensable. The question of how such data should be compiled will have a crucial impact on costs. A classical top-down approach of governmental agencies collecting data will likely not be feasible if REDD is to be implemented through local projects. Bottom-up citizen sensor approaches and web-based information from third party audits might lead (in such a scenario) to information disclosure. On the contrary, if REDD is to be implemented through national REDD programs, the existing statistical apparatus might be sufficient to handle additional REDD monitoring requirements.

REDD monitoring as part of GEO

Global initiatives e.g. the Group on Earth Observations (GEO), claim that better international cooperation in the collection, interpretation, and sharing of EO information is an important and cost-effective mechanism for improving information available to decision makers. Fritz et al. [57] asked how the benefits of EO can be assessed to justify the additional investment required to facilitate international collaboration, data sharing, linking the current observing systems and to reach interoperability among the current observing systems. They proposed a "benefit chain" concept, based on the logic that an incremental improvement in the observing system (including its data collection, interpretation and information-sharing aspects) will result in an improvement in the quality of decisions based on that information.

In this paper we assess costs of REDD monitoring. These include information that are available from implemented or planned projects and monitoring companies (the latter to a smaller degree). In the case that information from REDD projects could be fed into GEO and contribute to the Global Earth Observation System of Systems (GEOSS), benefits for society could be manifold. Therefore, some of the REDD costs could be offset by benefits to the forestry sector and potentially to many other of the societal benefit areas such as water, health, energy, disaster, biodiversity, ecosystems, climate and weather.

Applied to the case of REDD policy and monitoring requirements, the benefit chain in REDD policy with respect to a better observing system could be described as follows: improved accuracy of monitoring of forest carbon stock changes leads to a better constraint on potential emissions from these forests and more realistic baselines, therefore giving the REDD process much more credibility overall, leading in the end to lower insurance costs.

One resulting question from the GEOSS perspective is how costs are going to be distributed globally in a REDD framework. An appropriate answer would probably require at least a general assessment of the potential distribution of the benefits. This will remain a major challenge.

Conclusions

The design of a REDD policy framework (specifically its rules), can have a substantial effect on monitoring costs. Nevertheless, many of the technical challenges of monitoring emissions from deforestation (and to a lesser extent degradation) are feasible. Moreover, costs of REDD monitoring are affordable and relatively low compared to other cost items that occur in REDD (often below 10% of total costs).

Future monitoring costs are likely to decrease because different sampling intensities will be used, project implementers can build on previous experience and existing data, and advances in technology will be available. If the advantages of co-benefits in other sectors (optimized land management, improved fire management, agricultural monitoring, etc.) are included in a cost benefit analysis, costs of REDD monitoring will further decrease. Considering REDD as part of a Global Earth Observation System of Systems (GEOSS) will help to realize these benefits.

International cooperation is, however, needed to overcome initialization costs, unequal access to monitoring technologies and know-how.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

HB coordinated the work on this paper, designed structure and concept and is the major contributor to the text. KE provided data and substantially contributed to several paragraphs of the manuscript. GK helped with critical revision and literature input. SF and FK incorporated the links to the GEO process. IM provided literature and data and helped drafting paragraphs of this paper. MO had the idea, contributed to the design of the study and critically reviewed the manuscript. All authors read and approved the final version of the manuscript.

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References

1. Meridian Institute: **Reducing Emissions from Deforestation and Forest Degradation (REDD): An Options Assessment Report.** Prepared for the Government of Norway; 2009.
2. Grassi G, Monni S, Federici S, Achard F, Mollicone D: **Applying the conservativeness principle to REDD to deal with the uncertainties of the estimates.** *Environmental Research Letters* 2008, **3:**.
3. Gibbs HK, Brown S, Niles JO, Foley JA: **Monitoring and estimating tropical forest carbon stocks: Making REDD a reality.** *Environmental Research Letters* 2007, **2:**.
4. Hansen MC, Stehman SV, Potapov PV, Loveland TR, Townshend JRG, DeFries RS, Pittman KW, Arunarwati B, Stolle F, Steininger MK, Carroll M, DiMiceli C: **Humid tropical forest clearing from 2000 to 2005 quantified by using multitemporal and multiresolution remotely sensed data.** *Proceedings of the National Academy of Sciences of the United States of America* 2008, **105:**9439-9444.
5. Achard F, Defries R, Eva H, Hansen M, Mayaux P, Stibig HJ: **Pan-tropical monitoring of deforestation.** *Environmental Research Letters* 2007, **2:**.
6. Estrada Porrúra M, Corbera E, Brown K: **Reducing greenhouse gas emissions from deforestation in developing countries: revisiting the assumptions.** Tyndall Centre for Climate Change Research, UK; 2007.
7. Herold M, Johns T: **Linking requirements with capabilities for deforestation monitoring in the context of the UNFCCC-REDD process.** *Environmental Research Letters* 2007, **2:**.
8. Nabuurs GJ, Masera O, Andrasko KP, Benitez-Ponce Boer R, Dutschke M, Elsiddig EJ, Ford-Robertson Frumhoff P, Karjalainen T, Krankina O, Kurz W, Matsumoto M, Oyhantcabal W, Ravindranath NH, Sanchez MJS, Zhang X: **Forestry.** In *Climate change 2007: Mitigation. Contribution of Working group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* Edited by: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press; 2007.
9. UNFCCC: **Report on a workshop on reducing emissions from deforestation in developing countries.** *Note by the Secretariat. FCCC/SBSTA/2006/10* 2006 [http://unfccc.int/resource/docs/2006/sbsta/eng/10.pdf].
10. Santilli M, Moutinho P, Schwartzman S, Nepstad D, Curran L, Nobre C: **Tropical deforestation and the Kyoto Protocol.** *Climatic Change* 2005, **71:**267-276.
11. Mollicone D, Achard F, Federici S, Eva H, Grassi G, Belward A, Raes F, Seufert G, Stibig H-J, Matteucci G, Schulze E-D: **An incentive mechanism for reducing emissions from conversion of intact and non-intact forests.** *Climatic Change* 2007, **83:**477-493.
12. UNFCCC: **Reducing emissions from deforestation in developing countries: approaches to stimulate action.** *Submissions from Parties. FCCC/CP/2005/Misc.1. Geneva* 2005 [http://unfccc.int/resource/docs/2005/cop11/eng/misc01.pdf].
13. FAO: **Global Forest Resources Assessment 2005. Progress towards sustainable forest management.** Food and Agriculture Organization of the United Nations, Rome; 2006.
14. UNFCCC: **Background paper for the workshop on reducing emissions from deforestation in developing countries. Part I: Scientific, socioeconomic, technical and methodological issues related to deforestation in developing countries. Workshop on reducing emissions from deforestation in developing countries. 30 August – 1 September 2006.** United Nations Framework Convention on Climate Change, Rome, Italy; 2006.
15. Asner GP, Broadbent EN, Oliveira PJC, Keller M, Knapp DE, Silva JMM: **Condition and fate of logged forests in the Brazilian Amazon.** *Proceedings of the National Academy of Sciences of the United States of America* 2006, **103:**12947-12950.
16. Mollicone D, Achard F, Federici S, Eva HD, Grassi G, Belward A, Raes F, Seufert G, Stibig HJ, Matteucci G, Schulze ED: **An incentive mechanism for reducing emissions from conversion of intact and non-intact forests.** *Climatic Change* 2007, **83:**477-493.
17. GOFC-GOLD: **Reducing greenhouse gas emissions from deforestation and degradation in developing countries: a sourcebook of methods and procedures for monitoring, measuring and reporting.** GOFC-GOLD report version COP13-2; 2008.
18. UNFCCC: **Ad Hoc Working Group on Long-term Cooperative Action (AWG-LCA): Revised negotiating text.** UNFCCC, FCCC/AWGLCA/2009/INF.1; 2009.
19. UNFCCC: **Cost of implementing methodologies and monitoring systems relating to estimates of emissions from deforestation and forest degradation, the assessment of carbon stocks and greenhouse gas emissions from changes in forest cover, and the enhancement of forest carbon stocks.** UNFCCC, Technical report FCCC/TP/2009/1; 2009.
20. Huettner M, Leemans R, Kok K, Ebeling J: **A comparison of baseline methodologies for 'Reducing Emissions from Deforestation and Degradation'.** *Carbon Balance and Management* 2009, **4:**4.
21. Fritz S, Havlik P, Schneider U, Schmid E, Obersteiner M: **Uncertainties in Global Land Cover Data and its Implications for Climate Change Mitigation Policies Assessment.** *Proceedings of the International Symposium on Remote Sensing of Environment, Stresa, May 2009* 2009.
22. IPCC: **Good Practice Guidance for Land Use, Land-Use Change and Forestry.** Hayama, Japan, IPCC/OECD/IEA/IGES; 2003.
23. Böttcher H, Freibauer A, Obersteiner M, Schulze ED: **Uncertainty analysis of climate change mitigation options in the forestry sector using a generic carbon budget model.** *Ecological Modelling* 2008, **213:**45-62.
24. Neeff T, Henders S: **Guidebook to markets and commercialization of forestry CDM projects.** Tropical Agricultural Research and Higher Education Center, CATIE, Turrialba, Costa Rica; 2007.
25. Newcombe K, Janson-Smith T, Schlamadinger B, Havemann T, Emmer I, Paustian K, Brown S, Pedroni L: **Voluntary Carbon Standard – Guidance for Agriculture, Forestry and Other Land Use Projects.** *VCS, Voluntary Carbon Standard* 2008.
26. Trines E, Höhne N, Jung M, Skutsch M, Petsonk A, Silva-Chavez G, Smith P, Nabuurs G-J, Verweij P, Schlamadinger B: **Integrating agriculture, forestry and other land use in future climate regimes: Methodological issues and policy options.** In *WAB Report 500102002* Netherlands Environmental Assessment Agency, Bilthoven, the Netherlands; 2006.
27. DeFries R, Achard F, Brown S, Herold M, Murdiyarso D, Schlamadinger B, de Souza C Jr: **Earth observations for estimating greenhouse gas emissions from deforestation in developing countries.** *Environmental Science and Policy* 2007, **10:**385-394.
28. DeFries R, Achard F, Brown S, Herold M, Murdiyarso D, Schlamadinger B, DeSouza C: **Reducing greenhouse gas emissions from deforestation in developing countries: Considerations for monitoring and measuring. Report of the Global Terrestrial Observing System (GTOS) number 46.** GOFC-GOLD report 26; 2006.
29. Goetz S, Baccini A, Laporte N, Johns T, Walker W, Kellndorfer J, Houghton R, Sun M: **Mapping and monitoring carbon stocks with satellite observations: a comparison of methods.** *Carbon Balance and Management* 2009, **4:**2.
30. Duveiller G, Defourny P, Descleìe B, Mayaux P: **Deforestation in Central Africa: Estimates at regional, national and landscape levels by advanced processing of systematically-distributed Landsat extracts.** *Remote Sensing of Environment* 2008, **112:**1969-1981.
31. Desclee B, Bogaert P, Defourny P: **Forest change detection by statistical object-based method.** *Remote Sensing of Environment* 2006, **102:**1-11.
32. Santoro M, Beer C, Shvidenko A, McCallum I, Wegmueller U, Wiesmann A, Schmullius C: **Comparison of forest biomass estimates in Siberia using spaceborne SAR, inventory-based information and the LPJ dynamic global vegetation model.** In *ESA ENVISAT Symposium, 23–27 April* Montreux, Switzerland; 2007.
33. Wagner W, Luckman A, Vietmeier J, Tansey K, Balzter H, Schmullius C, Davidson M, Gaveau D, Gluck M, Toan TT, Quegan S, Shvidenko A, Wiesmann A, Yu JJ: **Large-scale mapping of boreal forest in SIBERIA using ERS tandem coherence and JERS backscatter data.** *Remote Sensing of Environment* 2003, **85:**125-144.
34. Imhoff ML: **Radar backscatter and biomass saturation: ramifications for global biomass inventory.** *IEEE Transactions on Geoscience and Remote Sensing* 1995, **33:**511-518.
35. McRoberts RE, Tomppo EO: **Remote sensing support for national forest inventories.** *Remote Sensing of Environment* 2007, **110:**412-419.
36. Magnusson M, Fransson JES, Holmgren J: **Effects on estimation accuracy of forest variables using different pulse density of laser data.** *Forest Science* 2007, **53:**619-626.

37. Patenaude G, Hill RA, Milne R, Gaveau DLA, Briggs BBJ, Dawson TP: **Quantifying forest above ground carbon content using LiDAR remote sensing.** *Remote Sensing of Environment* 2004, **93:**368-380.
38. DeFries R, Achard F, Brown S, Herold M: **Reducing greenhouse gas emissions from deforestation in developing countries: considerations for monitoring and measuring. Outcome of GOFCGOLD workshop on monitoring tropical deforestation for compensated reductions.** GOFC-GOLD Report No. 26, GTOS Report No. 46; 2006.
39. DeFries RS, Houghton RA, Hansen MC, Field CB, Skole D, Townshend J: **Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s.** *Proceedings of the National Academy of Sciences of the United States of America* 2002, **99:**14256-14261.
40. Van Laake PE, Sànchez-Azofeifa GA: **Focus on deforestation: Zooming in on hot spots in highly fragmented ecosystems in Costa Rica.** *Agriculture, Ecosystems and Environment* 2004, **102:**3-15.
41. Morton DC, DeFries RS, Shimabukuro YE, Anderson LO, Del Bon Espirito-Santo F, Hansen M: **Rapid assessment of annual deforestation in the Brazilian Amazon using MODIS data.** *Earth Interactions* 2005, **9:**1-22.
42. Achard F, Eva HD, Stibig H-J, Mayaux P, Gallego J, Richards T, Malingreau J-P: **Determination of deforestation rates of the world's humid tropical forests.** *Science (Washington DC)* 2002, **297:**999-1002.
43. Lehtonen A, Makipaa R, Heikkinen J, Sievanen R, Liski J: **Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests.** *Forest Ecology and Management* 2004, **188:**211-224.
44. Wirth CJ, Schumacher Schulze ED: **Generic biomass functions for Norway spruce in Central Europe – a meta-analysis approach toward prediction and uncertainty estimation.** *Tree Physiology* 2004, **24:**121-139.
45. Nogueira EM, Fearnside PM, Nelson BW, Barbosa RI, Keizer EWH: **Estimates of forest biomass in the Brazilian Amazon: New allometric equations and adjustments to biomass from wood-volume inventories.** *Forest Ecology and Management* 2008, **256:**1853-1867.
46. Segura M, Kanninen M: **Allometric models for tree volume and total aboveground biomass in a tropical humid forest in Costa Rica.** *Biotropica* 2005, **37:**2-8.
47. Schlamadinger B, Ciccarese L, Dutschke M, Fearnside PM, Brown S, Murdiyarso D: **Should we include avoidance of deforestation in the international response to climate change?** In *Carbon forestry: who will benefit? Proceedings of Workshop on Carbon Sequestration and Sustainable Livelihoods* Bogor, Indonesia, CIFOR; 2005.
48. Fritz S, McCallum I, Schill C, Perger C, Grillmayer R, Achard F, Kraxner F, Obersteiner M: **Geo-wiki.org: The use of crowdsourcing to improve global land cover.** *Remote Sensing* 2009, **1:**345-354.
49. Skutsch M, van Laake PE: **Redd as multi-level governance in-the-making.** *Energy and Environment* 2008, **19:**831-844.
50. Skutsch MM: **Reducing carbon transaction costs in community-based forest management.** *Climate Policy* 2005, **5:**433-443.
51. Stern N: **Stern Review: the Economics of Climate Change.** HM Treasury, Cambridge University Press, UK; 2006.
52. Eliasch Review: **Climate Change: Financing Global Forests.** Report to UK government, commissioned by the Prime Minister and prepared by Johan Eliasch with the support of the Office of Climate Change, London; 2008.
53. Osborne T, Kiker C: **Carbon offsets as an economic alternative to large-scale logging: a case study in Guyana.** *Ecological Economics* 2005, **52:**481-496.
54. Nepstad D, Soares-Filho B, Merry F, Moutinho P, Rodrigues HO, Bowman M, Schwartzman S, Almeida O, Rivero S: **The costs and benefits of reducing carbon emissions from deforestation and forest degradation in the Brazilian Amazon.** Woods Hole Research Center, Falmouth, MA, USA; 2007.
55. Grieg-Gran M: **The cost of avoiding deforestation.** International Institute for Environment and Development (IIED), London; 2008.
56. Kindermann G, Obersteiner M, Sohngen B, Sathaye J, Andrasko K, Rametsteiner E, Schlamadinger B, Wunder S, Beach R: **Global cost estimates of reducing carbon emissions through avoided deforestation.** *Proceedings of the National Academy of Sciences of the United States of America* 2008, **105:**10302-10307.
57. Fritz S, Scholes RJ, Obersteiner M, Bouma J, Reyers B: **A conceptual framework for assessing the benefits of a Global Earth Observation System of Systems.** *Systems Journal, IEEE* 2008, **2:**338-348.
58. GTZ: **Reducing Emissions from Deforestation in Developing Countries. The way forward.** Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), Eschborn; 2007.
59. Skutsch M, Bird N, Trines E, Dutschke M, Frumhoff P, de Jong BHJ, van Laake P, Masera O, Murdiyarso D: **Clearing the way for reducing emissions from tropical deforestation.** *Environmental Science and Policy* 2007, **10:**322-334.
60. Patenaude G, Milne R, Dawson TP: **Synthesis of remote sensing approaches for forest carbon estimation: reporting to the Kyoto Protocol.** *Environmental Science and Policy* 2005, **8:**161-178.
61. Tilley BK, Munn IA, Evans DL, Parker RC, Roberts SD: **Cost Considerations of Using LiDAR for Timber Inventory.** *Southern Forest Economics Workers. Online papers* 2004.
62. Parker RC, Evans DL: **Stratified light detection and ranging double-sample forest inventory.** *Southern Journal of Applied Forestry* 2007, **31:**66-72.
63. IPCC: **Special Report: Land-use, Land-use Change and Forestry.** Cambridge, Cambridge University Press; 2000.
64. FAO: **NFMA approach and process: an analysis of Cost and Time.** In *National Forest Monitoring and Assessment Working Paper NFMA 39* Food and Agriculture Organization of the United Nations, Rome; 2008.
65. UNFCCC: **Investment and Financial Flows to Address Climate Change. Background report.** UNFCCC; 2007.
66. UNFCCC: **Investment and Financial Flows to Address Climate Change – an Update.** UNFCCC, Technical report FCCC/TP/2008/7; 2008.

6 The effects of climate policy on the energy–technology mix: an integrated CVaR and Real Options approach

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1 Introduction

As more evidence about the contribution of anthropogenic GHG emissions to the rate of global warming and the associated damages is brought forward,[1] the debate of whether climate policy should be implemented has shifted towards a different focus. More precisely, the debate centres now around the right policy *instrument* that should be implemented to achieve the desired reduction in emissions before irreversible damages accumulate.

While European countries have introduced a cap and trade system called the European Trading Scheme (ETS), other countries have argued that the resulting CO_2 price will be volatile and therefore detrimental to their industries' profitability. Other suggestions include taxes that could be escalating or constant. If CO_2 prices were deterministic, the height of the threshold, beyond which investment into more environmentally friendly technologies would be triggered, would depend solely on the level of the CO_2 price and its projected rate of growth.

So there are multiple instruments that policy makers can implement to reduce GHG emissions. In this chapter we model such policy as a CO_2 penalty, which could be a tax or a permit price and focus on the effect that volatility in CO_2 prices has on investment at the firm level and how this translates to changes in the aggregate mix of energy technologies. In order to tackle this problem, we first optimize the timing of adopting and operating a technology (e.g. a coal-fired power plant with the flexibility to add a carbon capture module, which can be switched on and off) with a real options model, where both the price of electricity and also CO_2 charges are stochastic. This generates a return distribution, which can then be used as an input to a portfolio model, where the risk measure is the Conditional Value at Risk (CVaR). For both volatile and (relatively) stable CO_2 prices, we thus obtain return distributions corresponding to different technologies: fossil-fuel-fired power generation (in the form of a coal-fired power plant) and renewable energy (in the form of an onshore wind farm). Furthermore, we include biomass-fired generation with carbon capture and storage (CCS) because it is an interesting case, since the biomass that needs to be grown for the combustion process sequesters more CO_2 than is ultimately emitted when using CCS, which leads to negative emissions.

Moreover, facing large uncertainty not only about the CO_2 policy as such, but also about many other factors that influence the climate and the energy system, we think that it is important to analyze how the results differ between scenarios, which represent alternative future developments of population and demographics, economic growth and the rate of technological progress. Such scenarios have been developed in IIASA's GGI Database (2007) and provide shadow prices for GHG emissions, which can be used as CO_2 prices in the real options model. We do not only test for changes in investment in the three different scenarios provided in this database, but we also investigate the policy implications of different stabilization targets. More information about these scenarios will be presented when the data used are introduced in Section 3.1.

The results show that the new method of integrating real options with portfolio optimization delivers new insights into investment decision-making under uncertainty. Moreover, the application to climate change policy reveals that return distributions indeed depend on the volatility of the CO_2 price (which remains unspecified and could be a continuously updated tax or the price of a permit) and that such volatility can also work in favor of the policy goals, i.e. make the policy itself more effective.

In this chapter, we will first review the corresponding literature—real options theory, portfolio selection and different risk measures—in order to put our own contribution more into perspective. Then, we will describe the real options model, the data used and the results we obtain. Afterwards, we introduce the CVaR framework and present the results. A discussion of these results and possible policy implications follows. Finally, some extensions for future research are listed.

2 Literature review and contribution

2.1 Real Options theory in electricity planning

The electricity sector exhibits three special features: 1) the relative irreversibility of investments, since installing new equipment involves large sunk costs, 2) the uncertainty surrounding the investment decisions, and 3) the flexibility of timing investments, so that investment can be postponed or brought forward in time, as new information becomes available. Real options theory provides a framework, in which investment under uncertainty can be investigated when irreversibility and flexibility with respect to the timing of sequential decisions are involved.

Even though options theory had originally been developed for valuing financial options in the 1970s (Black and Scholes, 1973, and Merton, 1973), option pricing was soon discovered to also provide considerable insight into decision-making concerning capital investment. Early frameworks were developed by McDonald and Siegel (1986), Pindyck (1988, 1991, 1993), and Dixit and Pindyck (1994). See Trigeorgis (1996) for a more comprehensive overview. More advanced and with several applications is Schwartz and Trigeorgis (2001).

The basic idea behind using options pricing for investments is that standard net present value calculations do not take into account that there might be a value of waiting in the face of uncertainty about the future evolution, for example, of prices, policies or costs in general. Regarding the opportunity to defer an investment as an option means that we can assign a value to waiting. In other words, investors gain more information about the uncertainty that surrounds economic decisions as time passes by. Therefore, staying flexible by postponing decisions has an option value if the degree of uncertainty is large enough. This value increases if the involved sunk costs are high or if uncertainty increases. In this case it pays off to wait and see how the conditions have changed, especially if they are expected to be rather stable afterwards.

Real options studies, which analyze investment behaviour in the electricity sector are numerous and focus on very different issues: Dixit and Pindyck (1994, pp. 51–54) show in their book how this approach can be useful to support decision-making in electricity planning. Tseng and Barz (2002), Hlouskova et al. (2005) and Deng and Oren (2003) amongst many others have analyzed the effects, for example, of variability in loads and the inclusion of specific operational constraints on investment. Recently, interest has shifted more to long-term planning again. One example is by Fleten et al. (2007) showing that investment in power plants relying on renewable energy sources will be postponed beyond the traditional net present value break even point when a real options approach with stochastic electricity prices is used. Madlener et al. (2005) develop a dynamic technology adoption model to incorporate multiple technologies in a kind of vintage setting, but they explicitly borrow elements from real options theory as well. A very recent article by Reinelt and Keith (2007) focuses on retrofitting existing fossil-fuel-fired capacity with CCS, which makes it similar to our framework.

A selection of some other interesting applications concern research financing, electricity trading and the importance of market structure. Davis and Owens (2003) optimize the amount of renewable energy R&D by valuing the potential savings from developing renewable energy in the face of fluctuating fossil fuel prices. Chaton and Doucet (2003) incorporate the trade of electricity and consider also demand and fuel price uncertainty, load duration curves and equipment availability. Keppo and Lu (2003) investigate how a large electricity producer forms his/her decision to produce some planned quantity of power and how this can affect the market price of electricity.

While investment optimization in a power plant or an incremental investment such as CCS is performed by the individual producer, large investors will typically want to invest in a technology *portfolio* rather than concentrate on a single technology or chain (e.g. coal plus CCS). Our contribution is to combine portfolio optimization with the results derived from our real options framework. In particular, we use the real options model to find the optimal investment strategy and its implied return distributions, which can then be employed as an input into the portfolio optimization. The next section therefore places our approach within the existing literature of portfolio optimization.

2.2 Portfolio theory and applications to energy investments

As much as the origins of real options theory are rooted in finance, the same is true for portfolio theory pioneered by Nobel laureate Markowitz (1952) and further developed by Merton (1969), Samuelson (1969) and Fama (1970). The theory starts out from the observation that most investors are risk averse, i.e. they refrain to a certain extent to buy assets that exhibit a large variance in their returns. To quote Markowitz himself, "[. . .] the investor does (or should) consider expected return a desirable thing and variance of return an undesirable thing," (Markowitz, 1952, p. 77). Investors thus compose their portfolios of assets that exhibit lower expected rates of return, but which are relatively secure, and of assets that have a high expected rate of return, for which they have to accept a higher level of variance. It is the tradeoff between expected return and variance that matters for the investor and leads to a diversification of the portfolio. The main result concerning this tradeoff is that investors should select portfolios that maximize expected returns given a pre-specified level of variance or minimize variance given a desired level of return or more.[2]

Later on, financial portfolio theory was adapted and applied to real assets as well. Examples include the valuation of offshore oil leases (Helfat, 1988) and the valuation of financing long-term projects. Applications involving energy planning date back as far as 1976 (Bar-Lev and Katz, 1976). Lately, interest in the topic has arisen again, see for example Awerbuch and Berger (2003), Awerbuch (2006) and Roques et al. (2006).

The study that is most closely related to ours is by Roques et al. (2006), who apply a mean-variance framework to UK diversification in electricity sector investment, where they include the risks associated with carbon price fluctuations and electricity price volatility beyond fuel price uncertainty that other authors have mainly been focusing on. Instead of optimizing at the firm level by using a real options model as we do, however, their return distributions are generated by net present value Monte Carlo simulations for three scenarios. The first scenario has independent, stochastic price processes, while the second scenario also takes into account that the price processes might be correlated. The third scenario has a fixed electricity price in order to assess the impact of long-term purchase contracts. In terms of their conclusions, it remains questionable whether the market can provide incentives to investors to opt for a socially optimal fuel mix. At the same time, it becomes apparent that the correlations between the price processes influence the results significantly.

Although the mean-variance (MV) approach by Markowitz (1952) explains diversification and the risk-return tradeoff in a very straightforward way, it has the disadvantage that it maximizes only quadratic utility, i.e. it is not a valid method to tackle problems involving preferences for higher-order return moments. As an example, return distributions might be skewed and have fat tails, which would imply higher losses beyond a certain threshold.[3] In fact, previous analysis has shown that—under carbon price and electricity price uncertainty—power plant return distributions are not necessarily normal (see Fortin et al. (2007)) and therefore the variance is not an appropriate measure of risk (see also Rockafellar and Uryasev, 2000). The results indeed differ significantly between the two approaches and CVaR is found to outperform MV on various accounts. In this chapter we want to address this shortcoming by using the Conditional Value-at-Risk (CVaR) as the risk measure and not the variance. The next section reviews the corresponding literature in more detail.

2.3 Mean-Variance vs (Conditional) Value-at-Risk

Even though MV portfolios are still used for risk management in financial institutions, some have started to employ other measures of risk, which capture extreme events providing information on the tail of a distribution. Two candidate risk measures are the Conditional Value at Risk (CVaR) and the Value at Risk (VaR), where the former is closely related to the latter and offers additional desirable properties. In order to explain the difference between the two measures, let us first define them carefully. The β-VaR of a portfolio is the lowest amount a such that, with probability β, the portfolio loss will not exceed α, whereas the β-CVaR is the conditional expectation of losses above that amount α, where β is a specified probability level.[4] This is illustrated in Figure 6.1, where it can clearly be seen that the β-VaR corresponds to the β-percentile of the distribution, whereas the β-CVaR is the mean of the random values exceeding VaR.

The shortcomings of VaR compared with CVaR relate to its usefulness in risk management and its technical properties. Losses exceeding the threshold value are not taken into account by VaR, but they are by CVaR. Moreover, VaR is only a coherent risk measure in the sense of Artzner et al. (1999), if distributions can safely be assumed to be normal. In contrast, CVaR is always a coherent risk measure, which is thus useful for a broader range of applications including those involving non-normal distributions. Furthermore, the results in Rockafellar and Uryasev (2000, 2002) make computational optimization of CVaR readily accessible. Note that, under certain conditions, the minimization of VaR and CVaR and the MV framework yield the same optimal portfolio allocations provided that underlying distributions

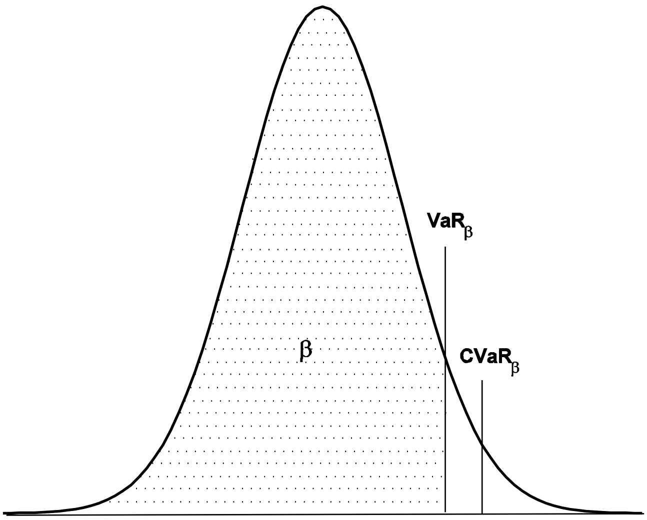

Figure 6.1 Illustration of β-VaR and β-CVaR for a normal loss distribution.

are normal.[5] This does not apply if the assumption of normality is violated. Fortin et al. (2007) have shown that, for the model that we also use here, the data and the parameter setting, "both the univariate distributions and the joint distribution (copula) of the returns, which are the results from the real options procedure, do not seem to be normal." As far as we know, combining real options with portfolio optimization using CVaR is a new approach and the application to climate change policy analysis is original as well. Recent literature that has undertaken steps into similar directions includes Doege et al. (2006), Fichtner et al. (2002), Spangardt et al. (2006), and Unger and Lüthi (2002).

In contrast to Fortin et al. (2007), who compare results for different levels of the CO_2 price, our focus is more on the impact of CO_2 price *volatility* on the composition of the generating portfolio. In addition, we want to see what the optimal portfolios are in scenarios that are based on different predictions about population growth, trade and technology proliferation, urbanization, migration, etc. For this purpose we make use of the GGI scenarios (IIASA, 2007), which will be described in more detail in the following section. Even though the results obtained are very intuitive, the numerical results for the individual technologies are supposed to be rather illustrative. The deeper purpose of this chapter is to illustrate the usefulness of this new approach for analyzing the impact of climate change policy and the associated uncertainty in different scenarios on the aggregate energy technology mix—and not to give ad hoc investment advice.

3 A Real Options framework for investment in power generation equipment

3.1 Model setup and technology data

This model is intended to determine the optimal investment plan for a single profit-maximizing electricity producer (or planner), who has to produce a specific amount of electricity but faces stochastic CO_2 and electricity prices.

In this chapter we consider a coal-fired and a biomass-fired power plant and a wind farm. The same real options framework is used to value the options to invest into them.[6] For the coal-fired and the biomass-fired power plants there is, in addition, the possibility to retrofit with CCS and to switch it on or off when the CO_2 fluctuates widely. Thereby we generate the return distributions for our CVaR model. The investor's decision problem is to maximize expected profits under uncertainty about future electricity and CO_2 prices. CO_2 prices, P^c_t, and electricity prices, P^e_t, are modelled as stochastic processes:

$$\ln P^c_t - \ln P^c_{t-1} = c + \varepsilon^c_t,$$
$$\ln P^e_t = c_1 + c_2 \cdot \ln P^e_{t-1} + \varepsilon^e_t \tag{6.1}$$

where $\varepsilon^c_t \sim N(0,(\sigma^c)^2)$ and $\varepsilon^e_t \sim N(0,(\sigma^e)^2)$, and the two disturbances are correlated with ρ as explained earlier.

So we can formulate the investor's decision problem as follows: x_t is the state variable describing whether the basic plant, the CCS module, or both have been built and whether the CCS module is currently running. Let a_t denote the action, i.e. the control variable. Possible actions are 1) building the power plant without the CCS module, 2) building the power plant with the CCS module, 3) adding the CCS module, 4) switching the CCS module off, 5) switching the CCS module on, and 6) doing nothing. $A(x_t)$ is the set of feasible actions. As a constraint, only feasible actions $a_t \in A(x_t)$ can be performed. The investor faces the following problem:

$$\max_{\{a_t\}_{t=0}^{T}} \sum\nolimits_{t=0}^{T} \frac{1}{(1+\gamma)^t} \cdot E[\pi(x_t, a_t, P^c_t, P^e_t)] \tag{6.2}$$

where starting values are known and γ is the discount rate (later set at 4 percent). The profit $\pi(\cdot)$ is income from electricity and heat production less the cost of fuel, CO_2 expenses, operational and maintenance (O&M) costs, and costs associated with a potential action, $c(a_t)$. We assume that the installed plant will produce continuously, thereby producing a fixed amount of output for a fixed amount of input each year.[7] The profit is:

$$\pi(x_t, a_t, P^e_t, P^c_t) = q^e(x_t) \cdot P^e_t + q^h(x_t) \cdot P^h - q^f(x_t) \cdot P^f_t - q^c(x_t) \cdot P^c_t - OC(x_t) - c(a_t) \tag{6.3}$$

where P^h is the heat price, P^f is the fuel price (which is zero for wind), OC is the O&M cost per year, and q^e, q^h, q^c, and q^f are the annual quantities of electricity, heat (which is zero for wind), CO_2 and fuel, respectively. We assume that installing a power plant implies its immediate use, but adding construction times does not change our qualitative results, if they do not differ immensely from each other.

The Bellman equation corresponding to the profit maximization in:

$$V(x_t, P_t^e, P_t^c) = \max_{a_t \in A(x_t)} \{\pi(a_t, x_t, P_t^e, P_t^c) + \frac{1}{(1+\gamma)^t} \cdot \tag{6.4}$$

$$E[V(x_{t+1}, P_{t+1}^e, P_{t+1}^c | x_t, P_t^e, P_t^c)]\}$$

with $V(\cdot)$ as the value function and $T = 50$ as the planning horizon. This problem can be solved recursively with dynamic programming techniques, where $E[V(x_{t+1}, P_{t+1}^e, P_{t+1}^c | x_t, P_t^e, P_t^c)]$ can be calculated either by means of partial difference equations, binomial lattices, or by Monte Carlo simulation. We use the latter (with 10,000 simulations) because it can easily be adapted when the framework is extended. Moreover, it remains computationally efficient for a high degree of complexity.

The solution of the recursive optimization part is a multidimensional matrix containing the optimal action at for every time period, state and price. We further refer to these optimum actions as "strategies." In order to analyze the final outcome, we simulate possible CO_2 and electricity price paths and extract the corresponding decisions from the output. By plotting the distribution of the optimal investment timing for all the different price paths, we obtain the final results.

Once we have thus derived the optimal decisions a_t, total discounted income and total discounted costs can be computed for realized outcomes and divided by each other to obtain the return (distribution), which is the used as an input to the portfolio optimization in Section 4.

Concerning the data, electricity prices are estimated from spot market data from the European Energy Exchange. The CO_2 prices are based on the projections for GHG shadow prices taken from IIASA's GGI Scenario Database (2007), where we consider three scenarios and both low and high stabilization targets for each one of them. The data used can be found in the Appendix, but we want to describe the scenarios briefly here to facilitate understanding and interpretation of the results subsequently.

The first scenario is the so-called "B1" scenario, which assumes a very optimistic outlook on future development: population peaks and starts to decline mid-century; there is much progress, which results in clean and resource efficient technologies, economies make a transition to service and information economies, and policies are geared towards social, economic and environmental sustainability. It can actually be observed that GHG prices can then even decrease towards the end of the projection period. In contrast, scenario "A2r" draws a much more pessimistic picture for the future, where fertilities do not converge in the near term and population increases substantially. Furthermore, economic development is very concentrated in specific regions and technological progress is slow and fragmented. Evidently, stabilization is not achieved easily and it turns out that a low stabilization target is not even feasible.

Finally, the third scenario, "B2", is a kind of "intermediary" scenario in the sense that technological change, population growth, economic development, etc. all lie in between the assumptions of B1 and A2r.[8]

Parameter estimates for the electricity price process as specified in Equation (1) are $c_1 = 1.655$, $c_2 = 0.541$, and $\sigma^e = 0.092$. For the CO_2 price process, c varies from scenario to scenario, but in general (with different starting values of the CO_2 price) the rate of increase is around 5 percent, and σ^c is tested for both a low value (1 percent) and a high value (10 percent) for the purpose of sensitivity analysis and because there is much uncertainty about future rates of volatility, which is the motivation of this exercise in the first place. The two noise processes are correlated with $\rho = 0.7$. Coal prices are assumed to remain constant throughout the planning horizon, which is reasonable for many countries looking at data acquired by the IEA (2005).[9] Another justification might be to assume that the producer engages in long term supply contracts for coal.

Technical data and costs for all technologies can be found in Table 6.1. These technologies are representative of fossil technologies (coal), less carbon-intensive technologies (biomass) and zero-emission renewables (wind). As the electricity output of the three plants (without CCS[10]) is the same, they are similar in size. We have conducted this "normalization" for the sake of comparability of the individual plants.

Table 6.1 Power plant data for coal, wind and biomass

Parameters	*Coal*	*Coal + CCS*	*Wind*	*Bio*	*Bio + CCS*
Technical features					
Electricity output [TWh/yr]	3,285	2,642	3,285	3,285	2,628
CO_2 emissions [kt CO_2/yr]	2,155	292	0	0	–2,691
Fuel consumption [TJ/yr]	23,188	23,188	0	29,565	29,565
Fuel cost [€/TJ]	1,970	1,970	0	1,692	1,692
O&M fixed cost [1,000 €/yr]	40,250	48,450	19,667	77,000	91,568
Installed capacity [MW]	500	402	1,389	500	400
Power efficiency [%]	46	37	27	40	32
Heat efficiency [%]	34	34	0	16	16
Heat price [€/TJ]	11,347	11,347	n/a	11,347	11,347
Capital costs					
Common parts [1,000 €]	686,500	686,500	n/a	402,029	402,029
Cost CCS module [1,000 €]		137,946			320,333
Total capital cost [1,000 €]	686,500	824,446	1,042,735	402,029	722,362

IEA/OECD (2005).

The high O&M costs of the biomass plant are due to the relative immaturity of the technology. Therefore, we allow for slight rates of technical change (3 percent), which lead these costs to drop until they eventually reach about the same magnitude as coal, which is technically very similar in O&M. Another peculiarity of the biomass plant is the zero (without CCS) and negative (with CCS) amount of emissions (see Table 6.1). This can be explained by the fact that biomass-based electricity production requires that additional biomass is grown, which will extract more CO_2 from the atmosphere, and we assume this to be subsidized or rewarded by extra CO_2 allowances. We assume that the amount of CO_2 emissions for a biomass plant without CCS technology is equal to these subsidies/allowances.[11]

3.2 Results from the Real Options approach

The results from valuing the above-mentioned investment and operational options are the return distributions that we will need for our portfolio optimization in the next section. Tables 6.2 and 6.3 report the relevant statistics of our return distributions for a strict and a less strict stabilization target respectively. The -VaR and -CVaR are computed for a confidence level of 95 percent and 99 percent respectively. More detailed explanations on CVaR as a risk measure can be found in Section 4.

Note also that for presentation purposes we have chosen to report -CVaR and -VaR, that is, instead of using (artificially made-up) losses, we refer to returns. -VaR of portfolio x at the significance level β is thus the (1-β)-quantile of the portfolio return, and -CVaR of portfolio x is the conditional expectation of portfolio returns given they are smaller than -VaR(x). Furthermore, -CVaR(x) ≤ -VaR(x), that is risk is *increasing* when -CVaR is *decreasing*.

Let us start with the "middle" scenario as a benchmark. In B2, for the strict stabilization target, we see that the -CVaR is larger in the low-volatility cases, which makes intuitive sense: like in an MV framework, more volatility leads to higher risk for all technologies, except for wind, which stays largely unaffected.

The neutrality of wind can be explained by the fact that it is not directly affected by CO_2 prices in the first place. If we see slight changes in other scenarios, these are due to the correlation of the noises of the electricity and CO_2 prices. Since electricity prices also affect wind returns, a marginal adjustment to the distribution also happens for wind, but most of the time these effects do not show up in the first three digits after the decimal point.

Another observation in the 480 ppm case in B2 is that expected returns are higher when volatility is large. This implies that for higher returns the investor needs to accept a higher risk in terms of -CVaR and lower risk can only be achieved at the expense of lower returns. These outcomes thus evidently warrant a portfolio optimization approach, which will be implemented in the following section.

Table 6.2 Descriptive statistics of return distributions of coal fired and biomass-fired power plants and of onshore wind mills for 95 percent confidence

	CO_2 price volatility	*Mean return*	*-CVaR*	*-VaR*
B1, 480 ppm				
Coal	high	1.770	1.686	1.719
Coal	low	1.755	1.726	1.714
Biomass	high	1.806	1.562	1.581
Biomass	low	1.794	1.728	1.712
Wind	high	1.815	1.727	1.705
Wind	low	1.815	1.727	1.705
B1, 670 ppm				
Coal	high	1.730	1.713	1.719
Coal	low	1.775	1.726	1.714
Biomass	high	1.644	1.594	1.581
Biomass	low	1.644	1.594	1.581
Wind	high	1.815	1.690	1.673
Wind	low	1.815	1.690	1.673
B2, 480 ppm				
Coal	high	1.508	1.449	1.435
Coal	low	1.499	1.462	1.453
Biomass	high	1.723	1.587	1.572
Biomass	low	1.644	1.648	1.634
Wind	high	1.815	1.727	1.705
Wind	low	1.815	1.727	1.705
B2, 670 ppm				
Coal	high	1.724	1.726	1.714
Coal	low	1.724	1.687	1.677
Biomass	high	1.644	1.594	1.581
Biomass	low	1.644	1.594	1.581
Wind	high	1.815	1.727	1.705
Wind	low	1.815	1.727	1.705
A2r, 670 ppm				
Coal	high	1.643	1.593	1.579
Coal	low	1.638	1.597	1.587
Biomass	high	1.650	1.592	1.580
Biomass	low	1.642	1.594	1.581
Wind	high	1.815	1.727	1.705
Wind	low	1.815	1.727	1.705
A2r, 820 ppm				
Coal	high	1.778	1.732	1.721
Coal	low	1.778	1.729	1.717
Biomass	high	1.644	1.594	1.581
Biomass	low	1.644	1.594	1.581
Wind	high	1.815	1.690	1.673
Wind	low	1.815	1.709	1.673

Results for scenarios B1, B2 and A2r with high and low CO_2 price volatility. Note that A2r is a scenario where stabilization at 480 ppm is not even possible, we compare 680 and 820 ppm instead.

Table 6.3 Descriptive statistics of return distributions for coal-fired and biomass-fired power plants and of onshore wind mills for 99 percent confidence

	CO_2 price volatility	*mean return*	*-CVaR*	*-VaR*
B1, 480 ppm				
Coal	high	1.770	1.666	1.633
Coal	low	1.755	1.706	1.697
Biomass	high	1.806	1.573	1.549
Biomass	low	1.794	1.701	1.689
Wind	high	1.815	1.705	1.673
Wind	low	1.815	1.705	1.673
B1, 670 ppm				
Coal	high	1.774	1.713	1.719
Coal	low	1.775	1.706	1.697
Biomass	high	1.644	1.572	1.562
Biomass	low	1.644	1.572	1.562
Wind	high	1.815	1.690	1.673
Wind	low	1.815	1.690	1.673
B2, 480 ppm				
Coal	high	1.508	1.426	1.414
Coal	low	1.499	1.470	1.440
Biomass	high	1.723	1.563	1.552
Biomass	low	1.644	1.604	1.612
Wind	high	1.815	1.690	1.673
Wind	low	1.815	1.690	1.673
B2, 670 ppm				
Coal	high	1.724	1.706	1.697
Coal	low	1.724	1.671	1.663
Biomass	high	1.644	1.572	1.562
Biomass	low	1.644	1.572	1.562
Wind	high	1.815	1.690	1.673
Wind	low	1.815	1.690	1.673
A2r, 670 ppm				
Coal	high	1.643	1.569	1.559
Coal	low	1.638	1.580	1.572
Biomass	high	1.650	1.571	1.562
Biomass	low	1.642	1.572	1.562
Wind	high	1.815	1.690	1.673
Wind	low	1.815	1.690	1.673
A2r, 820 ppm				
Coal	high	1.778	1.714	1.705
Coal	low	1.778	1.709	1.717
Biomass	high	1.644	1.572	1.562
Biomass	low	1.644	1.572	1.562
Wind	high	1.815	1.690	1.673
Wind	low	1.815	1.709	1.673

Results for scenarios B1, B2 and A2r with high and low CO_2 price volatility. Note that A2r is a scenario where stabilization at 480 ppm is not even possible, we compare 680 and 820 ppm instead.

Moreover, all scenarios show that expected return remains stable or decreases, while risk increases, as the confidence level ·β grows. This is because as the confidence level β rises, a larger part of the right tail of the distribution (namely 100·β percent) is captured and the conditional expected return from the smaller left tail (100(1 – β) percent) is maximized, which can also be seen in Figures 6.2 and 6.3 later in this section.

When we turn to other scenarios, however, we do not always see the same clear relationship between risk and volatility. In fact, the following explanations will demonstrate that this is because -CVaR is a risk measure providing much richer information about returns. In scenario B1 for the strict stabilization target, coal becomes *more risky* when volatility *decreases* for β = 95% and less risky when β = 99%, while biomass becomes less risky in both cases. It might seem counter-intuitive that coal should get more risky when volatility is lower, but a look at the change in the return distributions in Figure 6.2 explains this observation: Because the tail of the low volatility distribution is flatter at the 99 percent threshold than that of the high volatility distribution, the area to the left of the threshold is smaller and so is (CVaR) risk therefore. However, since the low volatility distribution is much more compact, the rise from 99 percent to 95 percent is much steeper than that of the high volatility distribution and the area left of 95 percent larger as a consequence. Note that the variance increases as intuition and theory suggest, so in an MV framework coal would always be more attractive in the low volatility situation. With the CVaR we can be more specific about the desired confidence level (and analyze its implications); and it is possible to capture information about the tail of the distributions as well.

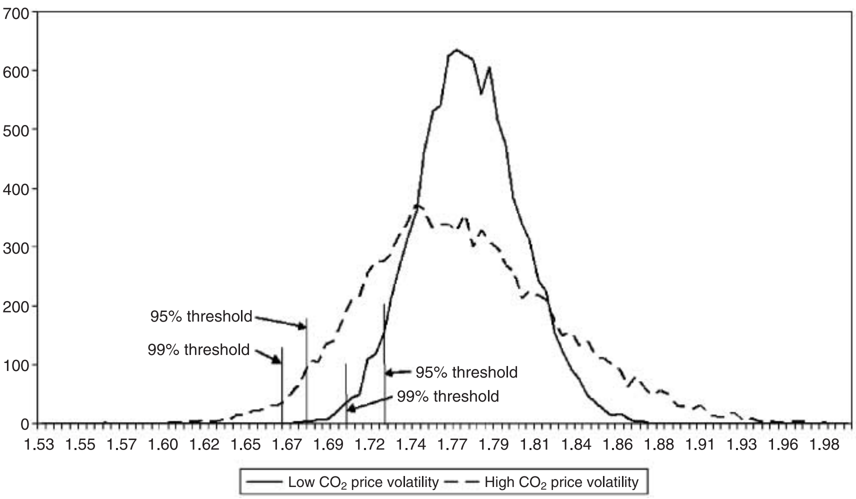

Figure 6.2 Coal return distributions for high and low volatility cases.

Note: The scenario is B1; stabilization target is 48 ppm.

For biomass, the high volatility distribution is not only wider than the low volatility distribution, but it is also more skewed, as can be seen in Figure 6.3. This is the reason why more volatility also always leads to more risk in terms of -CVaR for biomass in Tables 6.2 and 6.3. The reason behind the change in the shape of the distribution is that, with larger CO_2 price fluctuations, investment into the CCS module is triggered less often[12] and the investment dates are more spread out over time. However, the CCS module increases the returns from biomass substantially due to the credits received from "negative" emissions and with more cases without CCS there is also a higher frequency of low return outcomes.[13] In the case of coal the CCS module is always installed (though the investment date also spreads out as volatility increases), since CO_2 costs have to be equally borne in both high and low volatility situations, while biomass has zero emissions without CCS (because the growing of fuel biomass sequesters as much CO_2 as the combustion of biomass produces).

With a less strict target in both B1 and B2, the CCS module is never built for biomass and only sporadically for coal. As can be verified in Tables 6.2 and 6.3, both the -VaR and the -CVaR remain unchanged in these cases (because with zero emissions biomass is only marginally affected by σ^c via the correlation between the noises of the price processes). Moreover, less strict targets lead to higher coal returns and lower or stable biomass and wind returns for the obvious reason that CO_2 prices will be at lower levels, while risk generally declines.

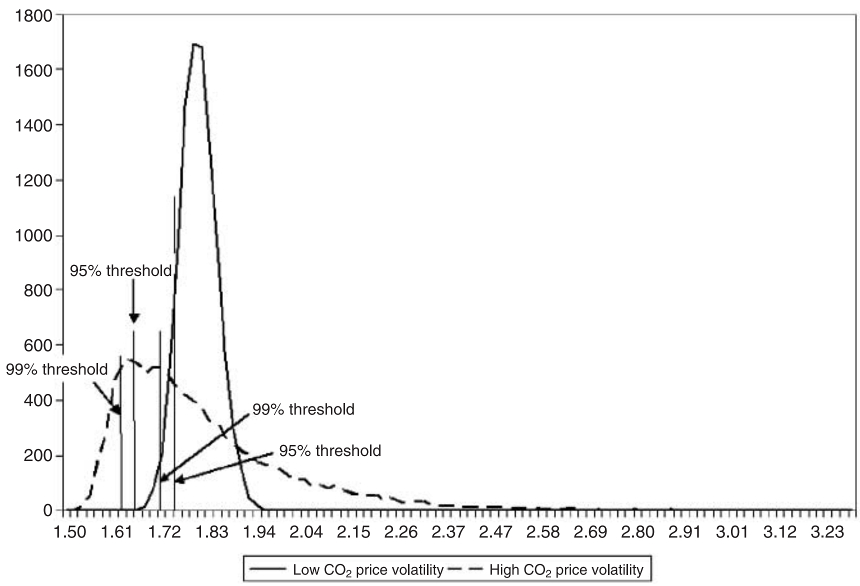

Figure 6.3 Biomass return distribution for high and low volatility cases.

Note: The scenario is B1; stabilization target is 480 ppm.

The highest expected return is that of wind, followed closely by biomass in B1, 480 ppm with high volatility. The reason for wind displaying such high expected returns is that in addition to the zero fuel costs, the wind farm owner does not face any extra costs in terms of CO_2 emissions. And since we observe the returns and not the profits, wind appears to be an attractive investment option in terms of expected return. Coal is the least risky technology in all scenarios when the less strict stabilization target applies. In B1, for the stricter target, wind outperforms coal in terms of risk when $\beta = 99\%$ and in B2, 480 ppm, coal is even more risky than biomass. This is also the case in the low stabilization target case in A2r. Remember that A2r is a pessimistic scenario, in which large CO_2 prices are needed to stabilize at a relatively low target, so coal is especially disadvantaged here. Let us now turn to the second part of this analysis—the portfolio optimization.

4 The CVaR model for the aggregate technology mix

4.1 The applied framework

Value-at-risk (VaR) is closely related to CVaR and still the more widely used risk measure as well. However, as briefly mentioned in Section 3, VaR has several disadvantages, discussed in e.g. Rockafellar and Uryasev (2000) and Palmquist et al. (2002). For the issue of VaR's coherency as a risk measure see Arztner et al. (1999) and Rockafellar and Uryasev (2002). Therefore, the number of CVaR applications has been growing quickly over the last years. Examples are in the area of energy risk management (Doege et al., 2006), crop insurance (Schnitkey et al., 2004 and Liu et al., 2006), power portfolio optimization (Unger and Lüthi, 2002), hedge funds applications (Krokhmal. et al., 2005), pension funds management (Bogentoft et al., 2001), and multi-currency asset allocations (Topaloglou et al., 2003).[14]

CVaR may be considered as an extension of VaR, as it provides a sort of approximation of VaR because it can be interpreted as an upper bound of VaR (see also Section 2.3). Minimizing CVaR instead of VaR in portfolio optimization might thus be seen as a more "conservative" approach. Moreover, CVaR makes more information available to the decision maker than VaR, since VaR denotes the maximum losses that an investor faces subject to some pre-specified probability (which corresponds to the most probable situation), while CVaR also provides information about the size of the potential losses in the case of the less probable event. In addition, CVaR is relatively easy to compute because the calculation can be reduced to a linear programming problem, which can effectively be solved using standard applied software available on the market. As Fortin et al. (2007) have shown, the assumption of normality cannot be defended for return distributions with the parameters that we also use here, so the application of CVaR will yield results different from as the traditional MV optimization.

Defining CVaR according to Rockafellar and Uryasev (2000), let $f(x,y)$ be the loss function depending on the investment strategy $x \in \mathbf{R}^n$ and the random vector $y \in \mathbf{R}^m$, and let $p(y)$ be the density of y. The probability of $f(x,y)$ not exceeding some fixed threshold level α is:

$$\psi(x, \alpha) = \int_{f(x,y) \leq \alpha} p(y)dy.$$

The β-VaR is defined by:

$$VaR_\beta(x) = \alpha_\beta(x) = \min \{\alpha | \psi(x, \alpha) \geq \beta\},$$

implying that, with probability β, losses will not exceed the threshold level $\alpha_\beta(x)$ for a given investment strategy x. The β-CVaR is finally defined by:

$$CVaR_\beta(x) = \varphi_\beta(x) = (1 - \beta)^{-1} \int_{f(x,y) \geq \alpha_\beta(x)} f(x, y)\, p(y)dy,$$

which is the expected loss given that the loss exceeds the β-VaR level, hence conditional expected loss, or conditional VaR, where the risk measure depends explicitly on the confidence level β. When clear from the context, we will drop β and x.

Looking back at Figure 6.1, the difference between VaR and CVaR as a risk measure becomes even clearer now: the β-VaR is the boundary of the shaded area of size β. The expected value of the losses beyond that boundary is the conditional value that is at risk. In other words, VaR is the threshold of the losses that will not be exceeded with the fixed probability β, it just refers to what is known with the probability β (called also confidence level). VaR does of course not convey any information about the magnitude of the losses that could be incurred beyond the confidence level. Let us assume we are interested in the assessment of some random value (possible loss) and we know with, say, 99 percent confidence the upper threshold (VaR). Knowing that information does not imply that we have any idea about what can be expected in case the threshold is exceeded, which will happen in 1 percent of the cases. Of course, this information may be extremely important for decision-making. The CVaR, as the expectation of the random value (in case it is exceeding the threshold -VaR), does take this into account, and thus contains additional useful knowledge. In this sense, CVaR outperforms VaR especially when the tail is "fat".

Both VaR and CVaR are applicable to returns as well as to losses, because one may consider returns as negative losses (and losses as negative returns). In the following, losses are defined as negative returns and thus we will report -VaR and -CVaR to indicate respectively the lower threshold for returns and expected returns in case they are lower than that threshold.

Let us consider n different technology chains that can be invested into. (In our application, for example, the first "chain" is a coal-fired power plant plus CCS, then we have a biomass-fired plant plus CCS as the second one and wind power as a single technology). Values y^i, $i = 1, \ldots, n$ reflect the return on investment (ROI) for each technology chain. We assume the vector $y = [y^1, \ldots, y^n]^T \in \mathbf{R}^n$ of ROIs to be a random vector having some distribution and describe the investment strategy using the vector $x = [x^1, \ldots, x^n]^T \in \mathbf{R}^n$ where the scalar value x^i, $i = 1, \ldots, n$ reflects the fraction of capital invested into technology i. The return function depends on the chosen investment strategy and the actual ROIs; computed as $x^T y$. As the actual ROI is unknown, there is a specific degree of risk associated with investment strategy x. To measure this risk and find the corresponding optimal x, our optimization is based on minimizing CVaR with a loss function $f(x,y)$ (i.e. negative returns):[15]

$$f(x, y) = -x^T y.$$

Following Rockafellar and Uryasev (2000) and Palmquist et al. (2002), we approximate the problem of minimizing CVaR by solving a piece-wise linear programming problem and reduce this to a linear programming (LP) problem with auxiliary variables. For both cases, a sample $\{y_k\}_{k=1}^{g}$, $y_k \in \mathbf{R}^n$ of the ROI distribution is used to construct the LP problem. Concerning the investment strategy in the sense that it should deliver a specified minimum expected return (or limited expected loss), the LP problem is equivalent to finding the investment strategy minimizing risk in terms of CVaR:

$$\min_{(x,\alpha,u)} \alpha + \frac{1}{q(1-\beta)} \sum_{k=1}^{q} u_k$$

$$s.t.\ e^T x = 1, m^T x \geq R, x \geq 0, u \geq 0, y_k^T x + \alpha + u_k \geq 0, k = 1, \ldots, q \qquad (6.5)$$

where $u = [u^1, \ldots, u^q]^T$, $u^k \in \mathbf{R}$, $k = 1, \ldots, q$ are auxiliary variables, $e \in \mathbf{R}^n$ is a vector of ones, q is the sample size, $m \in \mathbf{R}^n$ is the expectation of the ROI vector y, i.e. $m = E(y)$, R is the minimum expected portfolio return, α is a threshold of the loss function (and therefore also the upper bound of VaR) and β is a confidence level. (x_*, α_*) of the solution of equation (6.5) yields the optimal x_*, so that the corresponding β-CVaR reaches its minimum.[16]

In summary, we minimize CVaR-risk subject to a given expected return. In the experiments we conduct, we employ values for this required expected return R that are in fact not binding because we only want to study the impact of uncertainty and investment patterns across different scenarios to derive policy implications. Setting R high would exclude technologies that could have been interesting alternatives from the point of view of their risk profiles and we want to avoid this in our analysis. In the next section we present the results of computing VaR and CVaR for different levels of confidence β and different degrees of uncertainty σ^c across the scenarios described earlier.

4.2 Final results

In Table 6.4 we present the results from the portfolio optimization. Note that we are having a relatively low constraint on expected portfolio returns, *R*, so that it is indeed not binding.[17] Fortin et al. (2007) also investigate the effect of having different binding return constraints, but we want to focus on the composition, return and risk level of portfolios under different levels of CO_2 price volatility and in the different scenarios described above.

In addition, the maximum percentage that biomass and wind can attain in the complete portfolio is constrained to 20 percent each. The choice to introduce an "artificial" maximum capacity constraint is motivated by the fact that 100 percent wind and biomass portfolios are not feasible, even if desirable, for most countries owing to a lack of locations for efficient wind farms and lack of space to grow enough fuel for biomass-fired power generation. While we do not know if this 20 percent constraint is too small or too big as compared to reality, we think that it serves our illustrations quite well and that some countries might even be able to adopt higher portions of these renewables.

In terms of the results, we can generally confirm from the numbers in Table 6.4 that there is diversification as we go from low to high volatility cases, at least in the scenarios with ambitious stabilization targets. When these targets are less stringent, we either see portfolios that are composed of 80 percent coal and 20 percent wind (in B2) or portfolios that are completely coal-dominated (in B1 and A2r). This is of course due to low CO_2 prices and portfolio returns are indeed highest and (CVaR) risks lowest for these cases. Note also that increases in β lead to higher *portfolio* (CVaR) risk in the same way as individual CVaRs in the previous section. Intuitively, increasing the confidence level and thus decreasing the incidence of risk, the risk in terms of expected losses in the unfavorable case (CVaR) increases. By definition, the risk in terms of CVaR for single asset portfolios (with 100 percent coal, biomass or wind) increases with increasing confidence level β. So it not surprising that also the optimal portfolio risk increases with growing confidence level, which is exactly what the results show.

Let us now compare between scenarios in order to get an overview of the results of our analysis. As the lowest feasible stabilization target in A2r is 670 ppm, we choose this as our basis for comparison with B1 and B2. B1 portfolios have the highest expected return, followed by those of B2. The lowest return is that of A2r because the CO_2 price needed to stabilize at such a low target in such a scenario, where all factors make it difficult to save or even cut emissions, is much higher than in the other two cases. As a consequence, expected returns are much more vulnerable to fluctuations in CO_2 prices and the A2r portfolios also fare worst in terms of (CVaR) risk. B2 is less risky and B1 safest, according to the results in Table 6.4.

This seems to imply that investors and producers will suffer from lower returns and more risk, especially if they have such poor prospects as in the

Table 6.4 Optimal portfolio in terms of minimal risk for different levels of CO_2 price volatility and confidence levels

	β = 95%, high σ^c	β = 95%, low σ^c	β = 99%, high σ^c	β = 99%, low σ^c
B1, 480 ppm				
Coal	68.5	60.0	68.7	80.0
Biomass	11.5	20.0	11.3	0.0
Wind	20.0	20.0	20.0	20.0
R_e	1.783	1.775	1.783	1.763
-VaR	1.729	1.721	1.709	1.702
-CVaR	1.717	1.708	1.698	1.693
B1, 670 ppm				
Coal	100.0	100.0	100.0	100.0
Biomass	0.0	0.0	0.0	0.0
Wind	0.0	0.0	0.0	0.0
R_e	1.740	1.775	1.774	1.775
-VaR	1.730	1.726	1.713	1.706
-CVaR	1.719	1.714	1.703	1.697
B2, 480 ppm				
Coal	60.0	60.0	60.0	80.0
Biomass	20.0	20.0	20.0	0.0
Wind	20.0	20.0	20.0	20.0
R_e	1.612	1.604	1.612	1.604
-VaR	1.564	1.553	1.547	1.533
-CVaR	1.553	1.541	1.538	1.522
B2, 670 ppm				
Coal	80.0	80.0	80.0	80.0
Biomass	0.0	0.0	0.0	0.0
Wind	20.0	20.0	20.0	20.0
R_e	1.742	1.742	1.742	1.742
-VaR	1.699	1.688	1.682	1.667
-CVaR	1.689	1.675	1.673	1.656
A2r, 670 ppm				
Coal	64.1	80.0	64.9	80.0
Biomass	15.9	0.0	15.1	0.0
Wind	20.0	20.0	20.0	20.0
R_e	1.678	1.673	1.678	1.673
-VaR	1.637	1.624	1.620	1.603
-CVaR	1.627	1.611	1.612	1.593
A2r, 820 ppm				
Coal	100.0	100.0	100.0	100.0
Biomass	0.0	0.0	0.0	0.0
Wind	0.0	0.0	0.0	0.0

(*Continued*)

Table 6.4 Continued

	β = 95%, high σ^c	β = 95%, low σ^c	β = 99%, high σ^c	β = 99%, low σ^c
R_e	1.778	1.778	1.778	1.778
-VaR	1.733	1.729	1.714	1.709
-CVaR	1.721	1.717	1.705	1.700

The table reports portfolio allocations (in %) for coal, biomass and wind, expected returns R_e, -CvaR and -VaR. The constraint on the lower bound on expected portfolio returns is not binding, all scenarios feature a 20 percent capacity constraint on biomass and wind.

A2r scenario. And for tougher stabilization targets, returns will be even lower. Industry will thus oppose the imposition of strict stabilization targets in our framework. Can policy makers adopt a less stringent target and still meet their goal of increasing the share of renewable energy and thereby reducing emissions?

In order to answer this question, we have to analyze the scenarios in more detail. In A2r, with the strict stabilization target and β = 95%, the low volatility portfolios are composed of 80 percent coal and 20 percent wind, as wind is the most attractive technology, but is restricted to the maximum of 20 percent and biomass is the most risky technology to invest into. However, as volatility increases, biomass returns increase above those of coal and also the -CVaR becomes almost equal to coal's (see Table 6.2). Therefore, the share of biomass in the portfolio increases from 0 to 15.9 percent at the expense of coal. When β is raised, however, the -CVaR of biomass decreases again and the portfolio share of biomass is reduced to 15.1 percent. Note that the portfolio return is higher and the (CVaR) risk lower for the more diversified portfolios, which is in line with our expectations and opens up more favorable prospects for industry as well. Similar patterns can be observed in the other scenarios.

Policy makers can thus conclude that—as long as they are not too extreme—fluctuations in the price of CO_2 are not necessarily detrimental to the achievement of their policy goals. Quite on the contrary, we have just seen that such volatility can lead to diversification of energy portfolios and adoption of renewable energy technologies, even in a world with such pessimistic outlooks as the A2r scenario—provided that a relatively strict target is envisaged. The latter is necessary to provide a large enough CO_2 price level during the course of the planning period, which triggers investment into less carbon-intensive power generation equipment. While industry would want to opt for a less strict target, which would ensure higher returns that are also more certain to materialize, emissions will not be reduced sufficiently and actually increase in all scenarios, as coal continues to dominate the generation mix. In that case, the policy does not serve its own purpose and should be updated.

5 Summary and policy implications

From the above analysis, it can be concluded that the new integrated portfolio and real options approach is a valuable tool to investigate the effects of carbon price volatility and different predictions about future circumstances on investment decisions at the firm level. This information can help larger investors providing finance to individual power generation projects to form beliefs about the timing of decisions and the resulting return distributions, which can then be used in a portfolio optimization. At the same time, non-normality of these return distributions requires the introduction of a new risk measure, the Conditional Value-at-Risk, which helps to capture information about the tail of these return distributions.

In general, the results correspond to our expectations: for the strict stabilization target, larger volatility leads to more diversification, higher returns and lower risk in B1, B2 and A2r. For the less strict stabilization target this is not the case. As CO_2 prices do not reach the trigger levels of investment, coal (and in B2 also wind) is the cheapest technology and the portfolio composition remains unchanged at 100 percent coal.

For policy making this implies that if we live in a world where CO_2 emissions reductions happen easily, as in the B1 world, and stabilization targets are not so ambitious, then fluctuations in the price of CO_2 allow big investors to realize large returns at low (-CVaR) risk, whereas stricter policy encourages retrofitting and thereby reduces profitability and increases risk. On the other hand, the latter will make the policy more efficient in terms of achieving stabilization targets: with stricter targets we always see diversification and so the adoption of more renewable energy. So while industry might favor a loose target, no matter which predictions they believe in about B1, B2 and A2r conditions, policy makers should remain committed to targets that generate emissions prices that will be able to trigger the investment that is necessary to reduce emissions. In addition, volatility in CO_2 prices affects individual power plant owners and thus reshape the return distributions. Knowing this, large investors will diversify their portfolio and adopt more renewables. In other words, uncertainty at the firm level can make the policy designed to reduce emissions more successful, as the funds provided for energy generation are also spread out to biomass in our case.

Moreover, a larger confidence level generally makes portfolios more risky, which is self-explanatory by definition. If we want to interpret β as a kind of risk aversion measure, we may say that an increase in risk aversion in the face of large CO_2 price volatility leads to more diversification in the strict stabilization target situation in all three scenarios, which makes intuitive sense. With a less strict target this result does not hold, as has been mentioned before.

We think that this type of analysis opens up useful insights into investment dynamics. The optimal timing of investment and the exercise of investment and operational options are influenced by all kinds of price fluctuations. Here we have been focussing on electricity and CO_2 prices and on volatility in the growth of the latter in particular. Our framework is highly stylized and to be understood as a demonstration of a new methodology and its application to climate change policy. However, it has enabled us to investigate how volatility at the firm level affects investment and operational decisions and thereby returns, which then influences the beliefs of large investors, who will compose their portfolios accordingly. The following section will mention a few extensions that might be worthwhile to consider in future research.

6 Extensions

As the discussion above has shown, the integrated CVaR and real options approach is a useful tool in analyzing how optimum portfolios differ between different future scenarios and different policy parameters. However, our framework and also the data we use remain simple and rather general. On the one hand, this serves the purpose of illustrating a new methodology in a straightforward manner and free of too many interaction effects. On the other hand, we sacrifice a certain degree of realism. In order to apply the framework to specific situations, more details need to be taken into account and one should drop simplifying assumptions that could be decisive for the question at hand. For example, if construction times differ drastically between the technologies considered, this aspect has to be integrated into the real options model. Also during the portfolio optimization more constraints might be needed. In addition, other technologies that have other defining characteristics and are also associated with other risks need to be analyzed. Nuclear energy is one candidate: while it may be much less prone to suffer from CO_2 price increases, decommissioning problems and uncertainty about security and maintenance might reduce its attractiveness again.

On the methodological side, there is one important extension that will be needed for long-term planning, and that is a dynamic version of the portfolio model. This is not a straightforward task because there are issues of consistency between the two procedures and also problems of cross effects and interdependence. As an example, if we regard the portfolio optimizer to be a big investor providing finance to the individual power plant investor, then the latter might update his/her decision on the basis of the actions of the former, which will again trigger a change in the optimization on the part of the big investor and so forth.

Appendix

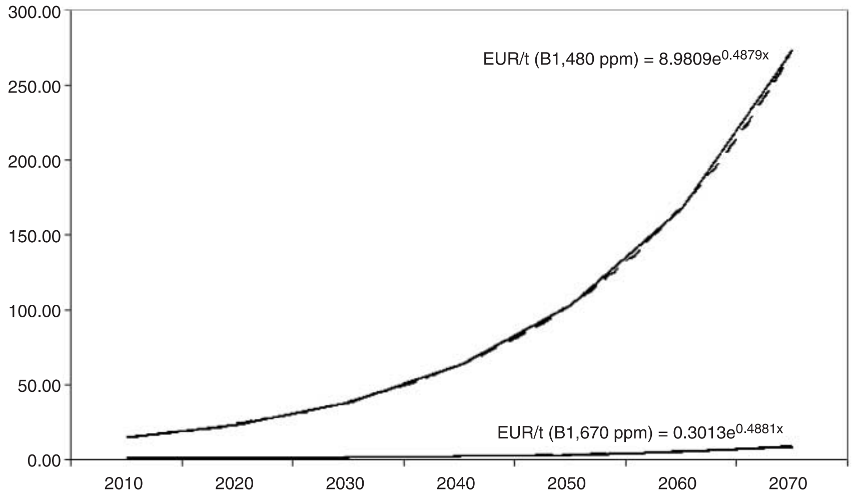

Figure 6A.1 Low population growth "optimistic" scenario.
Source: IIASA GGI database (2007).

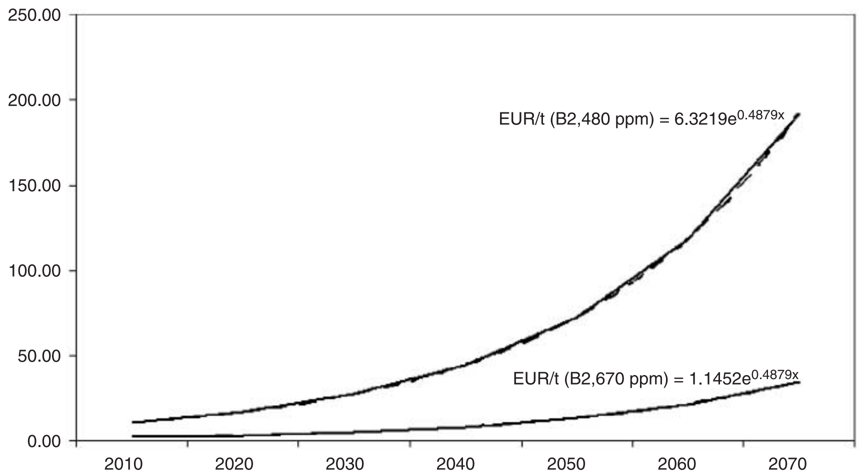

Figure 6A.2 "Intermediate" Scenario.
Source: IIASA GGI database (2007).

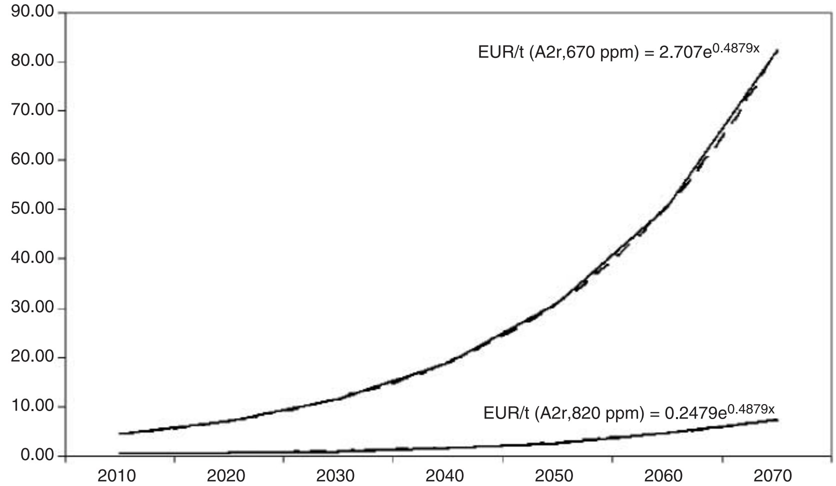

Figure 6A.3 High population growth "pessimistic" scenario.
Source: IIASA GGI database (2007).

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Notes

1 These damages involve, for example, the melting of the ice caps and glaciers leading to sea level rise and the destruction of the natural habitat of endangered species, ongoing desertification, more extreme weather situations involving higher intensity hurricanes, and many more (e.g. Knutson et al. (1998), Hulme and Kelly (1993), Overpeck et al. (2006), Rahmstorf (2007)).
2 See any standard textbook on portfolio theory for a more formal derivation of this result, e.g. Elton et al. (2003) or Brealey et al. (2005).
3 Furthermore, MV portfolios are myopic in the sense that the focus is on a portfolio at a single point in time. In electricity planning, planning periods of 30 years and more are usual, and dynamic developments call for a dynamic treatment of technology portfolios. While this problem has been tackled in the finance literature, these extensions are only applicable to financial assets. A study by van Zon and Fuss (2006) overcomes this problem by analyzing the generating portfolio in a vintage setting taking into account fuel and capital cost developments as well as fuel- and capital-saving technical change.
4 This definition only applies to continuous loss distributions. For the discrete case see Rockafellar and Uryasev (2002).
5 The CVaR approach can thus be viewed in some sense as a generalization of the MV approach when dealing with non-normal or non-symmetric distributions.
6 Note in particular that we value the investment options independently of each other, as otherwise the presence of the option to invest in one technology would influence the value of another, which would obscure the results of the portfolio

approach and therefore hamper our purpose to illustrate this new method in the most straightforward way.

7 Acknowledging that there are output contracts between distributors and generators, this assumption does not seem too strong.

8 See also Riahi et al. (2007) for a thorough description of these three scenarios and more details on the involved assumptions.

9 In any case, coal is not running out in the near future and thus leading to price increases due to scarcity, as thought in the past.

10 In the case where CCS is installed, output is lower due to lower efficiency, so producers will have to import the "deficit" at current spot market prices.

11 Uddin and Barreto (2007), amongst others, show that the negative emissions of a biomass-fired power plant with CCS are large, even if the decrease in efficiency, the extra emissions from the transport of biomass and CO_2 and many other factors are considered. According to their estimates, the emissions sequestered during the fuel growth phase are almost equal to the emissions produced by combusting it.

12 This refers to the number of Monte Carlo simulations for which investment is realized. The maximum number of times is thus 10,000.

13 In addition, the biomass CCS module is switched on and off much more frequently than the coal CCS module in the high volatility case.

14 See Fortin et al. (2007) for a more complete literature overview.

15 Note that minimizing the expected **right tail loss** (CVaR) is equivalent to maximizing the expected **left tail return** (-CVaR).

16 Problem (6.5) has efficiently been solved with GAMS (http://www.gams.com/) using the BDMLP and CONOPT solvers. The total number of equations in problem (5) is $q + n + 1$, the total number of constraints is $2q + n + 2$. The execution time for a sample size of $q = 10 \wedge 4$ on a Pentium D 3.4 GHz computer running Windows XP Professional Version 2002 Service Pack 2, using GAMS version 2.0.30.1 is less than two minutes. Note that the computational complexity is defined by the complexity of the underlying mathematical model, which produces the sample to be fed into the LP problem-solving module, i.e. the real options model.

17 The choice of R is of course arbitrary here and will depend on the preferences of the concerned investor in other applications. Selecting a higher R will require the investor to accept a higher level of risk in terms of CVaR at the same time, so the risk-return tradeoff known from standard portfolio theory still applies.

References

Artzner, P., Delbaen, F., Eber, J.-M. and Heath, D. (1999) "Coherent Measures of Risk." *Mathematical Finance*, 9, 203–228.

Awerbuch, S. (2006) "Portfolio-based Electricity Generation Planning: Policy Implications for Renewables and Energy Security". *Mitigation and Adaptation Strategies for Global Change*, 11(3), 693–710.

Awerbuch, S., M. Berger (2003) "Applying Portfolio Theory to EU Electricity Planning and Policy-Making." Working Paper EET/2003/03, Paris: International Energy Agency.

Bar-Lev, D. and Katz, S. (1976) "A Portfolio Approach to Fossil Fuel Procurement in the Electric Utility Industry." *Journal of Finance*, 31(3), 933–942.

Black, F. and Scholes, M. (1973) "The Pricing of Options and Corporate Liabilities." *The Journal of Political Economy*, 81(3), 637–654.

Bogentoft, E., Romeijn, H. and Uryasev, S. (2001) "Asset/Liability Management for Pension Funds Using CVaR Constraints." *Journal of Risk*, p. 57–71.

Brealey, R., Myers, S. and Allen, F. (2005) *Principles of Corporate Finance*, McGraw Hill, 7th edn.

Chaton, C. and Doucet, J. (2003) "Uncertainty and Investment in Electricity Generation with an Application to the Case of Hydro-Quebec." *Annual Operations Research*, 120(1), 59–80.

Davis, G., and Owens, B. (2003) "Optimizing the Level of Renewable Electric R&D Expenditures Using Real Options Analysis." *Energy Policy*, 31, 1,589–1,608.

Deng, S., and Oren, S. (2003) "Incorporating Operational Characteristics and Start-up Costs in Option-based Valuation of Power Generation Capacity." *Probability in the Engineering and Informational Sciences*, 17(2), 155–181.

Dixit, A. and Pindyck, R. (1994) *Investment under Uncertainty*. Princeton: Princeton University Press.

Doege, J., Schiltknecht, P. and Lüthi, H.-J. (2006): "Risk Management of Power Portfolios and Valuation of Flexibility." *OR Spectrum*, 28, 267–287.

Elton, E., Gruber, M. and Brown, S. (2003) *Modern Portfolio Theory and Investment Analysis*. New York: Wiley, 6th edn.

Fama, E. (1970): "Multiperiod Consumption-Investment Decisions." *American Economic Review*, 60(1), 163–174.

Fichtner, W., Göbelt, M. and Rentz, O. (2002) "Ein Modell zur strategischen Investitions- und Produktionsplanung bei Energieversorgern unter Berücksichtung von Unsicherheiten." *ZfE—Zeitschrift für Energiewirtschaft*, 26(3), 181–192.

Fleten, S., Maribu, K. and Wangensteen, I. (2007) "Optimal Investment Strategies in Decentralized Renewable Power Generation under Uncertainty." *Energy*, 32(5), 803–815.

Fortin, I., Fuss, S., Hlouskova, J., Khabarov, N., Obersteiner, M. and Szolgayova, J. (2007) "An Integrated CVaR and Real Options Approach to Investments in the Energy Sector." Economics series no. 209, Vienna: Institute for Advanced Studies. Available at http://www.ihs.ac.at/publications/eco/es-209.pdf.

Helfat, C. (1988) *Investment Choices in Industry*. Cambridge, MA: MIT Press.

Hlouskova, J., Kossmeier, S., Obersteiner, M. and Schnabl, A. (2005) "Real Options and the Value of Generation Capacity in the German Electricity Market." *Review of Financial Economics*, 14(3–4), 297–310.

Hulme, M., and Kelly, M. (1993) "Exploring the Links Between Desertification and Climate Change." *Environment*, 35.

International Energy Agency (IEA) (2005) *Projected Costs of Generating Electricity 2005 Update*, Paris: OECD/Nuclear Energy Agency.

International Institute of Applied Systems Analysis (IIASA) (2007): "GGI Scenario Database." Available at http://www.iiasa.ac.at./Research/GGI/DB/.

Keppo, J. and Lu, H. (2003) "Real Options and a Large Producer: the Case of Electricity Markets." *Energy Economics*, 25(5), p. 459–472.

Knutson, T., Tuleya, R. and Kurihara, Y. (1998) "Simulated Increase of Hurricane Intensities in a CO_2-Warmed Climate." *Science*, 279, p. 1,018–1,021.

Krokhmal, P., Uryasev, S. and Zrazhevsky, G. (2005) "Numerical Comparison of Conditional Value-at-Risk and Conditional Drawdown-at-Risk Approaches: Application to Hedge Funds." In *Applications of Stochastic Programming*, ed. S. Wallace, and W. Ziemba, MPS-SIAM Series on Optimization. Society for Industrial & Applied Mathematics.

Liu, J., Men, C., Cabrera, V., Uryasev, S. and Fraisse, C. (2006) "CVaR Model for Optimizing Crop Insurance under Climate Variability." Discussion paper, Risk

Management and Financial Engineering Lab, Department of Industrial and Systems Engineering University of Florida.

Madlener, R., Kumbaroglu, G. and Ediger, V. (2005) "Modelling Technology Adoption as an Irreversible Investment under Uncertainty: The Case of the Turkish Electricity Supply Industry." *Energy Economics*, 27(1), 139–163.

Markowitz, H. (1952): "Portfolio Selection." *Journal of Finance*, 7(1), 77–91.

McDonald, R., and Siegel, D. (1986): "The Value of Waiting to Invest." *Quarterly Journal of Economics*, 101, 707–723.

Merton, R.C. (1969): "Lifetime Portfolio Selection under Uncertainty: The Continuous-Time Case."*Review of Economics and Statistics*, 51(3), 247–257.

Merton, R. (1973): "The Theory of Rational Option Pricing." *Journal of Economic Management Science*, 4, pp. 141–183.

Overpeck, J., Otto-Bliesner, B., Miller, G., Muhs, D., Alley, R. and Kiehl, J. (2006) "Paleoclimate Evidence for Future Ice-sheet Instability and Rapid Sea-level Rise." *Science*, 311, pp. 1,747–1,750.

Palmquist, J., S. Uryasev, and P. Krokhmal (2002): "Portfolio Optimization with Conditional Value-at-Risk Objective and Constraints." *Journal of Risk*, 4(2).

Pindyck, R. (1988) "Irreversible Investment, Capacity Choice, and the Value of the Firm." *American Economic Review*, 79, 969–985.

Pindyck, R. (1991) "Irreversibility, Uncertainty and Investment." *Journal of Economic Literature*, 29, 1,110–1,152.

Pindyck, R. (1993) "Investments of Uncertain Cost." *Journal of Financial Economics*, 34, 53–76.

Rahmstorf, S. (2007) "A Semi-empirical Approach to Projecting Future Sea-level Rise." *Science*, 315, pp. 368–370.

Reinelt, P.S. and D.W. Keith (2007) "Carbon Capture Retrofits and the Cost of Regulatory Uncertainty." *Energy Journal*, 28, 101–127.

Riahi, K., Grübler, A. and Nakicenovic, N. (2007) "Scenarios of Long-term Socio-economic and Environmental Development under Climate Stabilization." *Technological Forecasting and Social Change*, 47, 887–935.

Rockafellar, R. and Uryasev, S. (2000) "Optimization of Conditional Value at Risk." *Journal of Risk*, 2, 21–42.

Rockafellar, R. and Uryasev, S. (2002) "Conditional Value at Risk for General Loss Distributions." *Journal of Banking and Finance*, 26, 1,443–1,471.

Roques, F., Newbery, D. and Nuttall, W. (2006) "Fuel Mix Diversification Incentives in Liberalized Electricity Markets: A Mean-Variance Portfolio Approach." Working Paper 2006/33, RCAS of the European University Institute: Florence School of Regulation.

Samuelson, P. (1969) "Lifetime Portfolio Selection by Dynamic Stochastic Programming." *Review of Economics and Statistics*, 51(3), 239–246.

Schnitkey, G., Sherrick, B. and Irwin, S. (2004) "The Performance of Conditional Value-at-Risk versus Value-at-Risk in Ranking Crop Insurance Alternatives." Discussion paper, Department of Agricultural and Consumer Economics University of Illinois at Urbana-Champaign.

Schwartz, E. and Trigeorgis, L. (2001) *Real Options and Investment under Uncertainty: Classical Readings and Recent Contributions*. Cambridge, MA: MIT Press.

Spangardt, G., Lucht, M., and Handschin, E. (2006) "Applications for stochastic optimization in the power industry." *Electrical Engineering*, 88, 177–182.

Topaloglou, N., Vladimirou, H. and Zenios, S. (2003) "CVaR Models with Selective

Hedging for International Asset Allocation." *Journal of Banking and Finance*, 26(7), p. 1,535–1,561.

Trigeorgis, L. (1996) *Real Options: Managerial Flexibility and Strategy in Resource Allocation*, Cambridge, MA: MIT Press.

Tseng, C. and Barz, G. (2002) "Short-term Generation Asset Valuation: A Real Options Approach." *Operations Research*, 50(2), 297–310.

Uddin, S. and Barreto, L. (2007) "Biomass-fired Cogeneration Systems with CO_2 Capture and Storage." *Renewable Energy*, 32, 1,006–1,019.

Unger, G. and Lüthi, H.-J. (2002) "Power Portfolio Optimization and the Importance of Operational Flexibility." Discussion paper, IFOR, ETH Zentrum.

Van Zon, A. and Fuss, S. (2006) "Irreversible Investment under Uncertainty in Electricity Generation: a Clay-Clay-Vintage Portfolio Approach with an Application to Climate Change Policy in the UK." Working Paper 2006–035, UNU-MERIT.

Agricultural adaptation to climate policies under technical change

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Agricultural adaptation to climate policies under technical change

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Keywords

Technical Change, Producer Adaptation, Agricultural Sector Model, Carbon Sequestration, Mathematical Programming, Climate Policy Simulation

Abstract

This study uses a partial equilibrium model of the US agricultural sector to examine how technical progress and carbon price levels affect land management adaptation. We find that the climate policy range, over which a more extensive agriculture is preferred, decreases as crop yields increase. Second, technical progress with traditional crops offers less mitigation benefits than progress with mitigation options themselves. Third, while agricultural producers benefit from technical progress on energy crops, they fare worse if technical progress improves traditional crops and low carbon prices.

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Numerous agricultural greenhouse gas emission mitigation options have been examined, experimented, and improved in the last two decades. Some argue that these options provide only a short term, low cost opportunity until a large set of emission friendly technologies are available in other sectors, particularly the energy sector (McCarl and Sands 2007). Others argue that consideration of non-greenhouse gas related environmental benefits suffices to make some mitigation strategies cost-effective even in absence of climate policies. For example, Lal (2004) documents substantial co-benefits of carbon sequestration.

Agricultural mitigation options may be grouped into three distinct categories: a) emissions reductions, b) carbon sinks, and c) emission offsets (McCarl and Schneider, 2000). Within each category, there are numerous independent, competitive, or complementary options. This study analyzes yet another option, which affects all three categories: technical progress. Generally, technical progress in agriculture may result in a combination of cost savings for a given production level or production increases for a given input level. An important benefit of yield increasing management consists of reduced resource requirements, particular for land. Lower land requirements relax land prices and therefore lower cost of land-based mitigation options such as afforestation or energy crop plantations.

The search for more efficient agricultural greenhouse gas emission mitigation options usually focuses on boosting energy crop yields or carbon sequestration rates in soils and trees but ignores conventional crop yields unless it relates to carbon saving systems like reduced tillage. However, from an economic point, there is no certainty that a 1 percent yield increase of say Miscanthus increases the agricultural greenhouse gas mitigation potential more than a 1 percent yield increase in conventionally tilled wheat. While the first option directly increases the emission offset potential per hectare, the second option decreases the opportunity cost across all land based mitigation options. Because the area shares of the affected crops might be very different, a small yield increase of a universally grown crop may be worth more than a large yield increase of a rare crop.

The objective of this study is to analyze how agricultural management adapts to climate policies and technical progress. Particularly, we want to examine whether the likely adaptation patterns change as crop production becomes more efficient. To do this we use the Agricultural Sector and Mitigation of Greenhouse Gas (ASMGHG) model and implement a general representation of technical change by assuming yield increases across certain crops without changes in production costs. One could, for example, interpret these general changes as the effects of genetic improvements. For the purpose of this study, a combined yield and cost adjustment would not yield additional insights because the effects of a low yield increase without cost change are similar to the effects of a higher yield improvement with increased costs.

Previous Studies

Numerous studies have examined the complex relations between agriculture, climate, and climate policies (Freibauer et al. 2004, Mall et al. 2006). Most studies focus on either climate change mitigation (Clemens and Ahlgrimm 2001, Smith and Almarez 2004) or climate change impacts. Few studies include both aspects (Olesen 2007). Agricultural climate impact studies address issues of yield and cost changes related to changes in CO_2 concentration, temperature, rainfall, and pest occurrence (Alexandrov et al. 2002, Tubiello et al. 2002). Climate mitigation studies generally comprise engineering (Wang and Dalal 2006, Cerri et al. 2007) or economic analyses (Pautsch et al. 2001, Antle et al. 2003, De Cara et al. 2005, Lubowski et al. 2006, Yoshimoto et al. 2007).

Engineering analyses exogenously prescribe management and technical changes and compute measures of technical potential (Cole et al. 1997, Phetteplace et al. 2001, Sartori et al. 2006, Smeets et al. 2007). These studies often contain a detailed representation of alternative technologies. Opportunity cost, market adjustments and their feedback on adaptation, however, are not accounted for and therefore estimated mitigation potentials are generally higher than those of economic analyses. The latter typically use much less technical detail on individual management options but portray competition and complementarities with other land uses and/or other potential mitigation options. The adaptation of land management often results from exogenous policy changes. Market adjustments are excluded in many regional economic studies which focus on the heterogeneity of farming conditions but - by assumption - use constant prices (for example Antle et al. 2003, De Cara et al. 2005, Lubowski et al. 2006). Analyses with endogenous prices (Schneider et al. 2007) come at the expense of a detailed account for spatial heterogeneity. This study uses this type of analysis and employs the ASMGHG model.

Previous ASMGHG applications have assessed economic emission mitigation potentials from land use and crop management changes. McCarl and Schneider (2001) show for relatively low carbon prices a domination of emission friendly crop management whereas higher prices attract more reductions through afforestation and bioenergy. Bioenergy options are investigated in more detail in Schneider and McCarl

(2003). Their study also shows how producer adaptations to climate policies change if the value of sink credits is discounted due to non-permanence. Adaptations also depend on the scope of climate policies, which may involve only a subset of all possible strategies. Schneider and McCarl (2005) illustrate how a policy directed only towards the energy sector will affect U.S. agriculture. Depending on the emission tax level and bioenergy refinery capacities, there will either be a switch to energy saving crop management or a combination of more intensive agriculture and bioenergy production. The impact of market feedbacks, adaptation choices, and other modeling assumptions has been studied by Schneider and McCarl (2006) and Schneider et al. (2007). Due to the large size of ASMGHG, all studies can only document a small selection of aggregated model output. This study will not only examine new aspects of agricultural greenhouse gas emission mitigation but also add insight to the interpretation of previous ASMGHG results.

The Agricultural Sector and Mitigation of Greenhouse Gas Model

The Agricultural Sector and Mitigation of Greenhouse Gas (ASMGHG) model represents US agriculture and trade relationships with foreign regions. The ASMGHG model is an expansion of the U.S. Agricultural Sector Model (ASM) (Chang et al. 1992, Chen 1999). It is a mathematical programming based, price-endogenous sector model of the agricultural sector, modified to include GHG emission accounting by Schneider (2000). ASMGHG also includes data on forestry production based on the FASOM model (Alig, Adams, and McCarl 1998). ASMGHG depicts production, consumption, and international trade in 63 U.S. regions for 22 traditional and 3 perennial energy crops, 29 animal products, 6 forest products and more than 60 processed agricultural products. Management choices include tillage, irrigation, fertilization, manure treatment, and animal feeding alternatives. Environmental accounts include levels of net GHG emission for CO2, CH4, and N2O; surface, subsurface, and groundwater pollution for nitrogen and phosphorous; and soil erosion.

ASMGHG simulates the market and trade equilibrium in agricultural markets of the United States and major foreign trading partners. Domestic and foreign supply and demand conditions are considered, as are regional production conditions and resource endowments. The market equilibrium reveals commodity and factor prices, levels of domestic production, export and import quantities, GHG emission management strategy adoption, resource usage, and environmental impacts.

Empirical Findings

This section describes the empirical findings of ASMGHG simulations with different assumptions about technological progress and climate policies. Technological progress is implemented as cost-free yield increase on a) all crops, b) annual food and fiber crops, or c) perennial energy crops. Furthermore, we assumed different levels of technological progress covering yield increases up to 50 percent. Climate policies are internalized via exogenous carbon equivalent prices on all greenhouse gas accounts in ASMGHG. Thus, while positive emissions are taxed, negative emissions are subsidized. To address the uncertainty of future climate policies, we use a price range between $0 and $500 per metric ton of carbon[1]. Combining the assumptions about yield increase,

[1] Note that the market price for carbon in the first stage of the EU emission trading system has been below 1 Euro per ton. However, for the second trading period, running from 2008 to 2012, higher prices are expected because a) the permit volume will be lower and b) permits will be auctioned. High carbon values are included in this study to examine the impact of strong carbon policies and to gain insight in the model results. These benefits outweigh the small computational costs of running additional scenarios.

crop scope, and climate policy results in 750 scenarios, where each scenario corresponds to a separate ASMGHG solution.

The output of a single ASMGHG solution already contains millions of endogenous variables values and accordingly higher is the output of 750 solutions. To present the simulation results within the scope of a journal article, we focus on selected, aggregate measures. The use of aggregates has two additional advantages beyond brevity. First, as argued in Onal and McCarl (1991), sector models, while using sub-state level data, perform better on the aggregated national level. This holds in particular for ASMGHG which is calibrated on the national level. Second, aggregate measures contain and summarize many individual measures simultaneously. To answer the research questions of this study, we examine the combined impact of technological progress and climate policy in US agriculture on a) crop management adaptation, b) greenhouse gas emission mitigation, c) agricultural emission intensities, and d) agricultural market and economic surplus changes.

Crop management adaptation

Agricultural mitigation efforts may involve either relatively strong land use changes towards forests or perennial energy crop plantations or relatively light management changes on existing cropping systems. In ASMGHG, possible adaptations of existing crop management include alternative crop, tillage, irrigation, and fertilization choices in each of the 63 regions. The environmental consequences of all included management alternatives are estimated exogenously and known before ASMGHG is solved. Particularly, soil carbon and nitrous oxide emission levels are estimated with the Environmental Policy Integrated Climate (EPIC) model. Emissions from machinery operation, fertilizer and pesticide manufacturing, water pumping, and grain drying were also included. Details on data sources and emission computations are given in Schneider and McCarl (2005).

To understand ASMGHG's results let us qualitatively review how a climate policy affects crop management in ASMGHG. The introduction of a carbon price acts as a tax on agricultural emissions and a subsidy on emission reductions. There are two principal adjustments: a) production with less average emissions per hectare and b) production with more emissions per hectare on less land. The first possibility implies a more extensive agriculture using for example lower nitrogen inputs with a reduced tillage system. Under a more extensive system, the total cultivated (arable) area could even moderately increase. The second possibility implies a more intensive agriculture, where traditional field crops are managed more intensively to achieve a certain level of commodity supply using less land. The "spare" area can then be used for high carbon mitigation strategies such as afforestation or energy crop plantations. Which of the two strategies prevails depends on the mitigation benefits (carbon price) and costs including both direct strategy and opportunity cost.

Figure 1 summarizes the simulated responses to greenhouse gas emission incentives in absence of technical progress. As shown, the assumed degree of climate policy has considerable impact on preferred crop management. Lower carbon prices related to weaker climate policies lead to an increase in arable land with decreases in irrigation and nitrogen intensity but a slight increase in tillage intensity. Particularly, the highest land use increase amounts to 3.6% in absence of technical progress and at a carbon price of $40 per MgCE. Special mitigation measures such as afforestation and energy crop plantations are not yet economically attractive. Overall, small mitigation incentives lead to a more extensive agriculture. For carbon prices above $50 per mega gram carbon equivalent (MgCE), adaptation reverses. Traditional agriculture becomes more intensive, therefore requiring less land. Energy crop plantations and new forests become attractive.

Technical progress leads to a faster switch to more intensive agriculture combined with high carbon yielding mitigation measures (Figure 2). First, with technical progress land demand decreases and so does the amount occupied by traditional crops. In absence of a carbon policy, a 50% yield increase of all crops decreases the area occupied by traditional crops by 8.5%. As yields increase, the share of irrigation increases. This, however, reflects the assumption that all yields were increased by the same factor. Since the original irrigated yields were higher than the related non-irrigated yields, the absolute yield increase is higher for irrigated than for non-irrigated crops. The water use per hectare averaged over the entire area occupied by traditional crops (including irrigated and non-irrigated fields) increases with technical progress. The net effect of technical progress on total water requirements is ambiguous. For most cases, our results show a decrease in total water requirements. In some cases (technical progress on all crops), however, technical progress leads to an increase in total water use.

Mitigation Potentials

Does technical progress increase greenhouse gas emission mitigation potentials from agriculture? Intuitively, the answer is yes because technological progress saves costs. However, ASMGHG simulations show that decreases are possible (Table 1). At a carbon price of $50 per MgCE, a 10% increase in traditional crop yields decrease the total agricultural mitigation potential by 3 Terra grams. Higher yields for traditional crops induce two competing effects on bioenergy and afforestation potentials. On one hand, these mitigation options become cheaper because land rents are lower when yields are higher. On the other hand, higher yields for traditional crops increase the opportunity cost for afforestation and bioenergy. The net effect is ambiguous and as shown can result in a slight reduction of mitigation potential.

Table 1 also shows that emissions from traditional agriculture are relatively little impacted. In all cases, the absolute change in emission mitigation is below 10 Terra grams of carbon equivalents. Mitigation through bioenergy and afforestation, however, changes more dramatically. For example, at a carbon price of $50 per MgCE, a 10% yield increase on all crops more than doubles the mitigation contribution from this account. Only for low carbon prices, i.e. prices below $30 per MgCE, technical progress with traditional crops outweighs progress with energy crops in terms of total agricultural mitigation contribution. However, this difference is relatively small and does not exceed 4 Terra grams of carbon equivalent. On the other hand, increases in energy crop yields outperform progress on traditional crops by far. For carbon prices above $30 per MgCE, a 50% yield increase on energy crops increases total mitigation 3 to 7 times more than under a 50% yield increase on all traditional crops. A 10% yield increase has similar effects.

Furthermore, one should note that the achievable mitigation volume is not a linear function of technical progress and carbon price. Over a considerable range there is only a moderate increase in mitigation potential due to technical progress. Particularly, for yield increases up to 10 percent and for carbon prices below $50 per tce, agricultural mitigation potentials shift very little. Higher yields in combination with high carbon prices, on the other hand, may have a non-proportional, large shift in mitigation potentials. For example, at a carbon price of $40 per MgCE, a 50 percent yield increase in all crops increases the agricultural mitigation potential by about 100%.

Agricultural Emission Intensities

A common misperception is that agricultural mitigation efforts imply reduced emissions per hectare. However, relevant for climate change mitigation are changes in total emissions. As discussed above, there are two principal ways to mitigate through agriculture. First, emissions must be decreased if agriculture uses the same or somewhat increased land base. Second, greenhouse gas emissions could also be reduced with increasing emissions per hectare if they are accompanied by a sufficiently large decrease in the associated land requirement. In essences, the question is whether agriculture should produce more intensively on less land or more extensively on the same land?

Table 2 provides insight from ASMGHG simulations into this issue. In absence of technical progress, average emission intensities for traditional crop and livestock activities decrease from more than 800 kg CE per hectare to about 500 kg CE per hectare. Above a carbon price of $50 per MgCE, intensities remain fairly constant. If emission intensities are calculated over the combined area for agriculture, energy crops, and afforestation, we find a continuous decrease in emissions with a zero balance around $100 per MgCE and negative net emissions thereafter. Technical progress increases the bifurcation between traditional agriculture and energy crop production. Thus, higher yields lead to higher emission intensities for traditional agriculture but at the same time higher mitigation intensities for energy crops.

Traditional agriculture becomes more intensive regardless if technical progress involves traditional crops or energy crops. If the genetic yield potentials for traditional crops increase, so do the marginal factor productivities related to irrigation, fertilization, and tillage. Hence, a shift towards higher factor intensities is preferred. On the other hand, if only energy crop yields increase, opportunity costs for traditional agriculture would increase and the transition towards energy crops would occur earlier, i.e. at a lower mitigation incentive. As energy crops increase in area, traditional agricultural commodity prices increase and cause an incentive for increased factor intensities.

Market and Welfare Changes

Adaptations in land use and crop management affect agricultural markets. Supply shifts lead to changes in commodity prices and economic surplus. While, greenhouse gas mitigation incentives tend to increase prices for traditional agricultural commodities, the opposite effect takes place with technical progress. The magnitude of price and surplus changes depends on elasticities of supply and demand. Consumer surplus changes due to supply shifts are closely linked to price changes. In theory, technical progress may increase or decrease producer surplus depending on whether the increased commodities supply effect outweighs the decreased price effect. In practice, continuous technical progress in US agriculture has decreased the real farm income over many decades after World War II. The effect of climate policies on producer surplus is even more ambiguous. On one hand, carbon prices cause increasing production costs, reduced supply, and increasing prices for traditional agricultural commodities. On the other hand, additional surplus can be generated through bioenergy production.

Table 3 shows quantitative estimates of producer and consumer surplus changes from ASMGHG simulations. These changes only include welfare changes in agricultural markets but do not include impacts of environmental changes. In absence of technical progress, agricultural producer surplus decreases for carbon prices up to $80 per MgCE but increases at higher emission mitigation incentives. For relatively low carbon prices, producers don't gain from technical progress. At higher carbon prices, this response reverses. Technical progress increases producer surplus. The strongest effect on producer surplus occurs under high carbon prices and high technical progress limited to energy crops. At higher carbon prices, progress on traditional crops seems to benefit producers more than progress on both traditional and energy crops. At lower carbon prices, exclusive progress on traditional crops hurts producers the most.

Consumers of agricultural commodities benefit from technical progress in traditional crops only for low or moderate carbon prices (Table 3). Higher emission mitigation incentives coupled with higher traditional crop yields lead to a higher share of energy crop plantations and thus may even increase prices for traditional agricultural commodities. The effect of increased energy crop yields is unambiguously negative for consumers across all carbon prices. The strongest negative impacts on consumers occur under high carbon prices and high technical progress limited to energy crops.

Conclusions

This study analyzes the costs of agricultural mitigation strategies and examines how technical progress and the intensity of climate policies affect land management adaptation. In absence of technical progress, we find for relatively modest carbon policies a shift towards a more extensive agriculture. This shift involves reduced fertilization and a smaller share of irrigated fields. The reduced emission intensity per hectare comes with a modest increase in total land under cultivation and an increase in tillage intensity. Stronger climate policies partially reverse this trend because energy crops and growing forests become an attractive, alternative land use option. However, additional forest and energy crop plantations are difficult to combine with an expanded area of traditional crops. The incentive and market price signals of stronger climate policies lead to a double strategy for agricultural lands. Non-food options with high carbon savings are combined with yield intensive agriculture on less land. Particularly, the share of irrigation increases. The optimal nitrogen intensity, however, is the outcome of a sensitive balancing act between N_2O and carbon emissions from nitrogen fertilizer use and emission offsets from additional energy crop plantations or forests made possible by higher yields with high fertilization.

The heterogeneous change of irrigation, tillage, and fertilization intensities across different carbon emission reduction incentives indicates a complex and non-linear nature of optimal land management responses to policies. This complex behavior can be simulated with data rich bottom-up models such as ASMGHG but may not be adequately captured with more general models, which condense management adaptations into a few constant substitution elasticities between agricultural inputs.

The interference between technical progress and agricultural adaptation to climate policies can be summarized in several points: First, the climate policy range, over which a more extensive agriculture is preferred, decreases as crop yields increase. This can be explained by the relatively inelastic demand for traditional agricultural products vs. perfectly elastic demand for carbon credits. Because higher yields require less land to produce the same output, marginal revenues for traditional commodities decline with technical progress while carbon revenues stay constant. Hence, technical progress decreases traditional cropland until marginal revenues are equal across all land management options. Second, our results show that technical progress on traditional crops hardly offers more mitigation benefits than progress with mitigation options themselves. Third, while agricultural producers benefit from technical progress with energy crops, they fare worse if technical progress improves traditional crops and low carbon prices. Depending on the income status of agricultural producers within society, the implied redistribution of welfare may or may not be welcome.

Several important limitations and uncertainties to this research should be noted. First, the findings presented here reflect technologies for which data were available to us. Second, most of the greenhouse gas emission data from the traditional agricultural sector are based on biophysical simulation models. Thus, the certainty of the estimates presented here depends on the quality of these models and the certainty of associated simulation model input data. Third, not internalized in this analysis were co-effects related to other agricultural externalities, costs or benefits of changed income distribution in the agricultural sector, and transaction costs of mitigation policies. Finally, all simulated results are derived from the optimal solution of the mathematical program and as such constitute point estimates without probability distribution.

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References

Alexandrov, V., J. Eitzinger, V. Cajic, and M. Oberforster (2002). "Potential impact of climate change on selected agricultural crops in north-eastern Austria." *Global Change Biology* 8(4):372–389.

Alig, R.J., D.M. Adams, and B.A. McCarl (1998). "Impacts of Incorporating Land Exchanges between Forestry and Agriculture in Sector Models." *Journal of Agricultural and Applied Economics* 30(2):389-401.

Antle, J., S. Capalbo, S. Mooney et al. (2003). "Spatial heterogeneity, contract design, and the efficiency of carbon sequestration policies for agriculture." *Journal of Environmental Economics and Management* 46(2):231-250.

Cerri, C.E.P., G. Sparovek, M. Bernoux et al. (2007). "Tropical agriculture and global warming: Impacts and mitigation options." *Scientia Agricola* 64 (1):83-99.

Chang, C.C., B.A. McCarl, J.W. Mjelde, and J.W. Richardson (1992). "Sectoral Implications of Farm Program Modifications." *American Journal of Agricultural Economics* 74:38-49.

Chen, C.C. (1999). "Development and Application of a Linked Global Trade-Detailed U.S. Agricultural Sector Analysis System." PhD Dissertation, Texas A&M University, May 1999.

Clemens, J. and H.J. Ahlgrimm (2001). "Greenhouse gases from animal husbandry: mitigation options." *Nutrient Cycling in Agroecosystems* 287-300.

Cole, C.V., I. Duxbury, J. Freney, O. Heinemeyer, K. Minami, A. Mosier, K. Paustian, N. Rosenberg, N. Sampson, and D. Sauerbeck (1997). "Global estimates of potential mitigation of greenhouse gas emission by agriculture." *Nutrient Cycling in Agroecosystems* 221-228.

De Cara, S., M. Houze, and P.-A. Jayet (2005). “Methane and Nitrous Oxide Emissions from Agriculture in the EU: A Spatial Assessment of Sources and Abatement Costs.” *Environmental & Resource Economics* 32:551-583.

Freibauer, A., M.D.A. Rounsevell, P. Smith et al. (2004). “Carbon sequestration in the agricultural soils of Europe.” *Geoderma* 122(1):1-23.

Lal, R. (2004). “Soil carbon sequestration impacts on global climate change and food safety.” *Science* 1623-1627.

Lubowski R.N., A.J. Plantinga, R.N. Stavins (2006). “Land-use change and carbon sinks: Econometric estimation of the carbon sequestration supply function.” *Journal of Environmental Economics and Management* 51(2):135-152.

Mall, R.K., Singh R., Gupta A. et al. (2006). “Impact of climate change on Indian agriculture: A review.” *Climatic Change* 78(2-4):445-478.

McCarl B.A. and R.D. Sands (2007) “Competitiveness of terrestrial greenhouse gas offsets: are they a bridge to the future?” *Climatic Change* 80(1-2):109-126

McCarl, B.A. and U.A. Schneider (2000). “US agriculture's role in a greenhouse gas emission mitigation world: An economic perspective.” *Review of Agricultural Economics* 22(1):134-159.

McCarl, B.A. and U.A. Schneider (2001). “Greenhouse gas mitigation in US agriculture and forestry.” *Science* 294(5551):2481-2482.

Olesen J.E. (2006). “Reconciling adaptation and mitigation to climate change in agriculture.” *Journal de Physique* IV 139:403-411.

Onal, H., and B.A. McCarl (1991). "Exact Aggregation in Mathematical Programming Sector Models." *Canadian Journal of Agricultural Economics* 39:319-334.

Pautsch, G.R., L.A. Kurkalova, B.A. Babcock et al. (2001). “The efficiency of sequestering carbon in agricultural soils.” *Contemporary Economic Policy* 19(2):123-134.

Phetteplace, H.W., D.E. Johnson, and A.F. Seidl (2001). “Greenhouse gas emissions from simulated beef and dairy livestock systems in the United States.” *Nutrient Cycling in Agroecosystems* 99-102.

Sartori F., R. Lal, M.H. Ebinger et al. (2006). „Potential soil carbon sequestration and CO2 offset by dedicated energy crops in the USA.” *Critical Reviews in Plant Sciences* 25(5):441-472.

Schneider, U.A. and B.A. McCarl (2003). “Economic potential of biomass based fuels for greenhouse gas emission mitigation.” *Environmental & Resource Economics* 24(4):291-312.

Schneider, U.A. and B.A. McCarl (2005). “Implications of a carbon-based energy tax for US agriculture.” *Agricultural and Resource Economics Review* 34(2):265-279.

Schneider, U.A. and B.A. McCarl (2006). “Appraising agricultural greenhouse gas mitigation potentials: Effects of alternative assumptions.” *Agricultural Economics* 35(3):277-287.

Schneider, U.A., B.A. McCarl, and E. Schmid (2007). “Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry.” *Agricultural Systems* 94:128-140

Smeets, E.M.W., A.P.C. Faaij, I.M. Lewandowski et al. (2007). “A bottom-up assessment and review of global bio-energy potentials to 2050” *Progress in Energy and Combustion Science* 33(1):56-106.

Smith, D.L. and J.J. Almaraz (2004). “Climate change and crop production: contributions, impacts, and adaptations.” *Canadian Journal of Plant Pathology* 26(3):253-266.

Tubiello, F.N., C. Rosenzweig, R.A. Goldberg et al. (2002). “Effects of climate change on US crop production: simulation results using two different GCM scenarios. Part I: Wheat, potato, maize, and citrus.” *Climate Research* 20(3):259-270.

Wang W.J., Dalal R.C. (2006). “Carbon inventory for a cereal cropping system under contrasting tillage, nitrogen fertilisation and stubble management practices.” *Soil & Tillage Research* 91(1-2):68-74.

Yoshimoto A and R. Marusak (2007). “Evaluation of carbon sequestration and thinning regimes within the optimization framework for forest stand management.” *European Journal of Forest Research* 126(2):315-329.

Table 1 Emission Mitigation and Changes due to Technical Progress [in TgCE]

Accounts	Carbon Price $/MgCE	Assumed Yield Increase 0%	All Crops 10%	All Crops 50%	Energy Crops 10%	Energy Crops 50%	Traditional Crops 10%	Traditional Crops 50%
Traditional Agriculture	0		+2	+3			+2	+3
	10	*52*		+4				+4
	20	*67*		+4				+4
	30	*75*	+3	+8		+2	+3	+7
	40	*85*		+6		+1		+5
	50	*96*	-2	+2		-1	-3	-2
	100	*112*		+2	+2	-1	+2	+2
	200	*122*	+2	+4		-6	+4	+6
	300	*138*	-1	-3	-2	-9	-1	+2
	500	*154*	+1	-3	-1	-8	+1	+1
Bioenergy and Afforestation	10			+8				
	20	*10*		+25		+4		+2
	30	*10*	+1	+87		+48		+5
	40	*10*	+4	+141	+4	+93	+1	+10
	50	*21*	+27	+183	+13	+129	-1	+20
	60	*43*	+32	+202	+23	+139	+6	+27
	70	*63*	+44	+203	+29	+157	+10	+37
	80	*92*	+37	+207	+28	+164	+4	+41
	90	*125*	+39	+210	+19	+153	+14	+32
	100	*139*	+42	+227	+29	+167	+11	+43
	125	*183*	+46	+234	+38	+181	+13	+33
	150	*209*	+57	+235	+40	+165	+14	+38
	200	*251*	+42	+221	+28	+154	+11	+36
	300	*273*	+48	+227	+30	+156	+14	+52
	500	*302*	+45	+220	+31	+153	+13	+53
All Accounts	0		+2	+3			+2	+3
	10	*52*		+12				+4
	20	*76*		+29		+4		+6
	30	*85*	+4	+95		+50	+3	+12
	40	*94*	+4	+147	+4	+94	+1	+15
	50	*117*	+25	+185	+13	+128	-3	+18
	60	*144*	+29	+202	+24	+140	+5	+24
	70	*166*	+44	+203	+30	+158	+11	+39
	80	*199*	+36	+207	+29	+161	+3	+41
	90	*235*	+41	+210	+19	+150	+16	+33
	100	*251*	+42	+228	+31	+166	+13	+46
	150	*329*	+55	+235	+41	+160	+16	+41
	200	*374*	+43	+225	+28	+148	+15	+42
	500	*456*	+46	+217	+30	+145	+15	+54

Table 2 Agricultural Emission Intensities and Additional Changes due to Technical Progress [in Kg CE/ha]

Accounts	Carbon Price	Assumed Yield Increase						
			All Crops		Energy Crops		Traditional Crops	
	$/MgCE	0%	10%	50%	10%	50%	10%	50%
Traditional Crop, Livestock	0	*816*	+2	+65			+2	+65
	10	*645*	+5	+54			+5	+55
	20	*592*	+3	+58		+2	+3	+54
	30	*562*	-4	+62		+9	-4	+45
	40	*533*	+8	+87	+3	+34	+6	+55
	50	*505*	+22	+112	+4	+50	+9	+71
	60	*498*	+30	+127	+7	+46	+16	+78
	80	*503*	+25	+135	+8	+72	+18	+67
	100	*510*	+23	+137	+5	+57	+6	+66
	200	*551*	+20	+132	+8	+62	+6	+68
	300	*517*	+37	+158	+8	+63	+39	+119
	500	*482*	+24	+141	+6	+43	+22	+128
Crop, Livestock, Bioenergy, Afforestation	10	*645*	+5	21			+5	+55
	20	*559*	+3	-43		-11	+3	+40
	30	*529*	-6	-270		-156	-5	+20
	40	*499*	-8	-438	-13	-285	+2	+9
	50	*432*	-75	-554	-42	-383	11	-20
	60	*345*	-86	-601	-72	-412	-10	-48
	70	*280*	-129	-602	-89	-457	-28	-101
	80	*181*	-106	-611	-85	-461	-5	-116
	90	*74*	-118	-618	-54	-424	-46	-95
	100	*28*	-120	-668	-88	-464	-37	-136
	125	*-115*	-124	-669	-99	-482	-36	-105
	150	*-189*	-154	-682	-114	-440	-47	-130
	200	*-315*	-122	-648	-77	-405	-45	-137
	300	*-420*	-133	-650	-73	-398	-43	-177
	500	*-546*	-134	-634	-79	-393	-48	-185

Table 3 Economic Surplus Changes due to Carbon Price and Additional Changes due to Technical Progress [in Mill $]

Accounts	Carbon Price $/MgCE	Assumed Yield Increase						
			All Crops		Energy Crops		Traditional Crops	
		0%	10%	50%	10%	50%	10%	50%
Producer Surplus Change	0		-3	-11			-3	-11
	10	*-3*	-3	-10	-3	-3	-6	-13
	20	*-5*	-3	-8	-5	-4	-8	-15
	30	*-7*	-3	-4	-7	-3	-10	-16
	40	*-8*	-2	+1	-7		-10	-16
	50	*-8*		+7	-7	+6	-10	-15
	60	*-7*	+1	+10	-4	+10	-9	-13
	70	*-4*	+2	+12		+18	-7	-11
	80	*-1*	+2	+14	+3	+22	-3	-8
	90	*3*	+2	+16	+8	+27		-5
	100	*7*	+2	+16	+11	+34	+4	-1
	125	*15*	+2	+24	+21	+50	+12	+6
	150	*25*	+3	+27	+32	+66	+21	+15
	200	*46*	+4	+35	+55	+98	+40	+33
	300	*87*	+11	+57	+101	+163	+83	+72
	400	*130*	+14	+77	+151	+229	+125	+113
	500	*172*	+18	+97	+197	+296	+168	+152
Consumer Surplus Change	0		+9	+31			+9	+31
	10		+9	+30			+9	+31
	20		+9	+29			+9	+31
	30		+9	+26		-3	+9	+29
	40	*-1*	+8	+23	-2	-7	+7	+28
	50	*-3*	+6	+19	-4	-13	+5	+25
	60	*-5*	+6	+19	-7	-17	+2	+22
	70	*-9*	+5	+19	-12	-24		+19
	80	*-13*	+5	+20	-16	-28	-6	+16
	90	*-18*	+7	+21	-21	-32	-9	+12
	100	*-23*	+7	+22	-25	-38	-13	+9
	125	*-30*	+7	+22	-34	-50	-21	+3
	150	*-40*	+8	+25	-44	-61	-29	-4
	200	*-59*	+9	+29	-63	-83	-45	-15
	300	*-91*	+8	+30	-97	-124	-77	-40
	400	*-122*	+9	+33	-131	-161	-106	-64
	500	*-151*	+10	+36	-161	-200	-133	-84

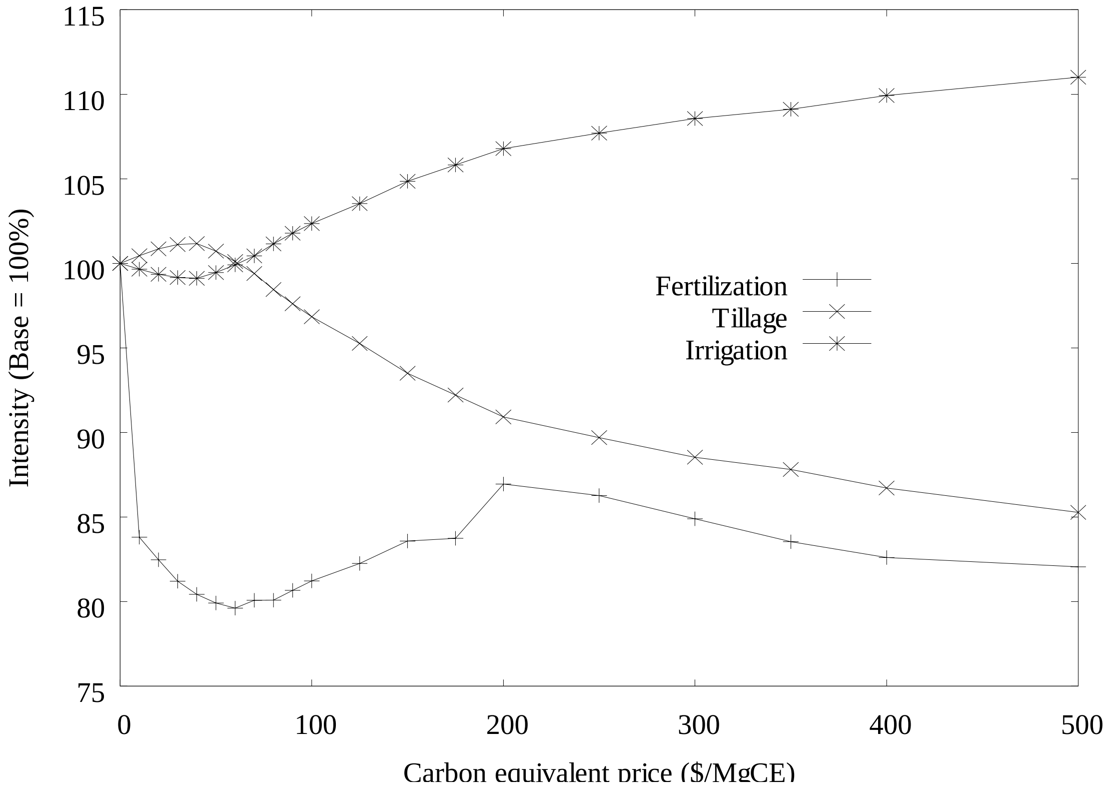

Figure 1 Adaptation of Crop Management under Climate Policy without Technical Progress

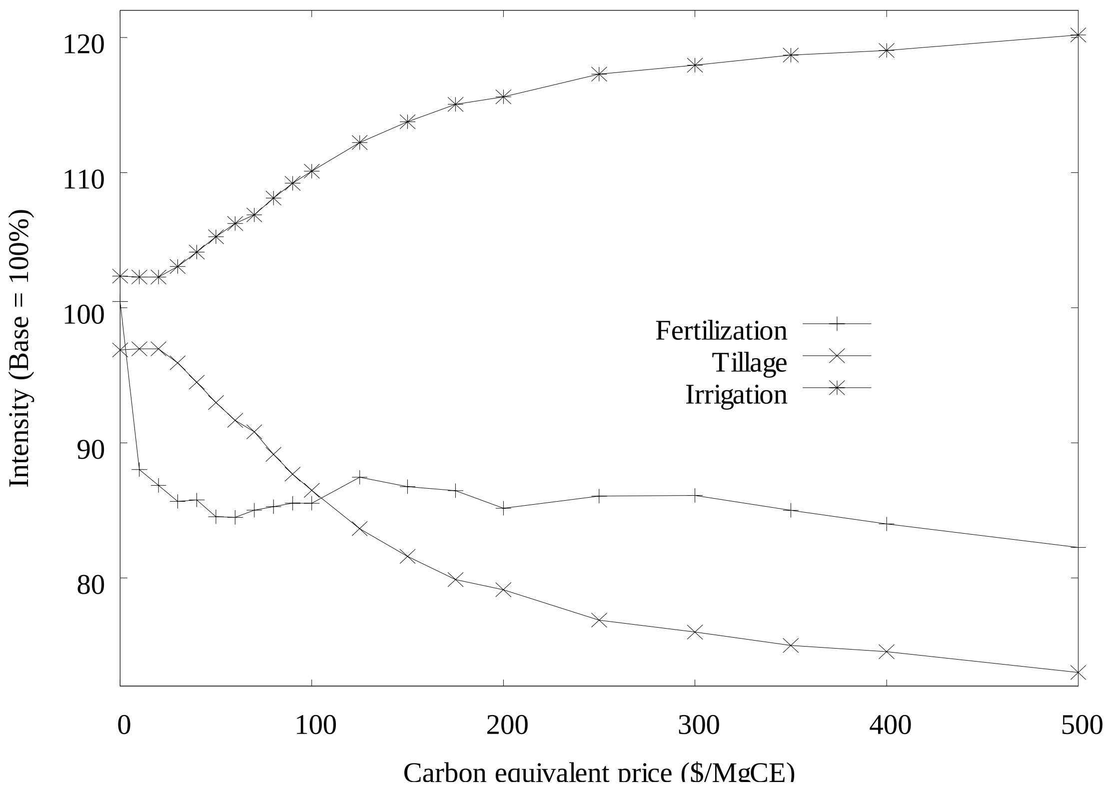

Figure 2 Adaptation of Crop Management under Climate Policy and 50% Yield Increases for all Crops

Appendix

Agricultural Price Indexes

Yield Increase	Carbon Price in $/MgCE	Livestock			Field Crops		
		Yield Increase assumed for					
		All Crops	Energy Crops	Annual Crops	All Crops	Energy Crops	Annual Crops
0PCT	0	1.00	1.00	1.00	1.00	1.00	1.00
	10	1.00	1.00	1.00	0.99	0.99	0.99
	20	1.00	1.00	1.00	0.98	0.98	0.98
	30	1.01	1.01	1.01	0.97	0.97	0.97
	40	1.03	1.03	1.03	0.97	0.97	0.97
	50	1.05	1.05	1.05	0.99	0.99	0.99
	60	1.08	1.08	1.08	1.02	1.02	1.02
	70	1.13	1.13	1.13	1.06	1.06	1.06
	80	1.17	1.17	1.17	1.10	1.10	1.10
	90	1.21	1.21	1.21	1.16	1.16	1.16
	100	1.27	1.27	1.27	1.21	1.21	1.21
	125	1.34	1.34	1.34	1.32	1.32	1.32
	150	1.48	1.48	1.48	1.43	1.43	1.43
	175	1.55	1.55	1.55	1.55	1.55	1.55
	200	1.66	1.66	1.66	1.67	1.67	1.67
	250	1.83	1.83	1.83	1.89	1.89	1.89
	300	2.03	2.03	2.03	2.15	2.15	2.15
	350	2.26	2.26	2.26	2.40	2.40	2.40
	400	2.45	2.45	2.45	2.64	2.64	2.64
	500	2.84	2.84	2.84	3.10	3.10	3.10
1%	0	1.00	1.00	1.00	1.00	1.00	1.00
	10	1.01	1.00	1.01	0.99	0.99	0.99
	20	1.01	1.00	1.01	0.99	0.98	0.99
	30	1.02	1.01	1.02	0.98	0.97	0.98
	40	1.03	1.03	1.03	0.98	0.97	0.98
	50	1.05	1.05	1.05	1.00	0.99	1.00
	60	1.08	1.08	1.08	1.03	1.02	1.02
	70	1.13	1.13	1.13	1.07	1.06	1.06
	80	1.17	1.17	1.17	1.11	1.11	1.10
	90	1.22	1.22	1.22	1.17	1.16	1.16
	100	1.28	1.27	1.28	1.22	1.22	1.22
	125	1.36	1.36	1.35	1.33	1.33	1.32
	150	1.50	1.48	1.50	1.45	1.44	1.44
	175	1.55	1.55	1.55	1.57	1.56	1.55
	200	1.67	1.67	1.66	1.69	1.68	1.67
	250	1.84	1.83	1.84	1.91	1.90	1.89
	300	2.04	2.03	2.04	2.16	2.16	2.15

	350	2.28	2.27	2.28	2.41	2.42	2.39
	400	2.48	2.46	2.47	2.69	2.66	2.67
	500	2.87	2.85	2.87	3.15	3.13	3.14
	0	1.00	1.00	1.00	1.00	1.00	1.00
	10	1.01	1.00	1.01	1.00	0.99	1.00
	20	1.02	1.00	1.02	0.99	0.98	0.99
	30	1.02	1.01	1.02	0.98	0.97	0.98
	40	1.03	1.03	1.03	0.98	0.97	0.98
	50	1.06	1.05	1.06	0.99	0.99	0.99
	60	1.09	1.08	1.09	1.03	1.02	1.02
	70	1.14	1.13	1.13	1.07	1.06	1.06
	80	1.18	1.17	1.18	1.12	1.11	1.10
2%	90	1.23	1.22	1.22	1.18	1.17	1.16
	100	1.29	1.28	1.28	1.22	1.22	1.22
	125	1.36	1.36	1.35	1.34	1.33	1.32
	150	1.51	1.48	1.50	1.45	1.44	1.43
	175	1.56	1.55	1.56	1.57	1.57	1.55
	200	1.68	1.67	1.67	1.70	1.69	1.68
	250	1.85	1.84	1.85	1.92	1.92	1.90
	300	2.05	2.03	2.05	2.16	2.17	2.14
	350	2.30	2.28	2.29	2.44	2.43	2.40
	400	2.49	2.47	2.48	2.71	2.68	2.67
	500	2.89	2.86	2.87	3.18	3.15	3.14
	0	1.00	1.00	1.00	1.00	1.00	1.00
	10	1.02	1.00	1.02	1.00	0.99	1.00
	20	1.03	1.00	1.03	0.99	0.98	0.99
	30	1.04	1.01	1.04	0.99	0.97	0.99
	40	1.05	1.03	1.05	0.99	0.97	0.99
	50	1.07	1.05	1.07	1.00	0.99	1.00
	60	1.12	1.09	1.12	1.04	1.03	1.03
	70	1.16	1.14	1.13	1.08	1.08	1.06
	80	1.21	1.17	1.21	1.14	1.13	1.11
5%	90	1.26	1.23	1.24	1.19	1.19	1.17
	100	1.32	1.28	1.30	1.24	1.23	1.21
	125	1.38	1.37	1.37	1.35	1.35	1.32
	150	1.53	1.48	1.52	1.47	1.46	1.43
	175	1.58	1.56	1.56	1.59	1.62	1.54
	200	1.70	1.68	1.70	1.72	1.72	1.68
	250	1.89	1.85	1.88	1.97	1.96	1.91
	300	2.10	2.04	2.08	2.23	2.21	2.16
	350	2.35	2.29	2.33	2.51	2.49	2.43
	400	2.54	2.49	2.52	2.75	2.74	2.68
	500	2.96	2.88	2.92	3.27	3.21	3.18
	0	1.00	1.00	1.00	1.00	1.00	1.00
10%	10	1.00	1.00	1.00	0.99	0.99	0.99
	20	1.01	1.00	1.01	0.98	0.98	0.98

	30	1.01	1.01	1.01	0.98	0.97	0.97
	40	1.04	1.04	1.03	0.99	0.98	0.99
	50	1.08	1.06	1.06	1.02	1.00	1.00
	60	1.13	1.09	1.10	1.06	1.05	1.03
	70	1.19	1.15	1.14	1.11	1.10	1.06
	80	1.22	1.18	1.21	1.16	1.16	1.12
	90	1.26	1.24	1.23	1.21	1.21	1.16
	100	1.32	1.28	1.29	1.26	1.26	1.20
	125	1.37	1.39	1.37	1.36	1.37	1.32
	150	1.53	1.48	1.50	1.50	1.50	1.42
	175	1.58	1.57	1.57	1.61	1.64	1.54
	200	1.70	1.69	1.68	1.75	1.76	1.66
	250	1.90	1.87	1.87	2.02	2.01	1.90
	300	2.12	2.07	2.12	2.32	2.28	2.18
	350	2.36	2.32	2.33	2.59	2.58	2.45
	400	2.55	2.52	2.50	2.85	2.84	2.69
	500	2.96	2.90	2.92	3.35	3.32	3.17
	0	1.00	1.00	1.00	1.00	1.00	1.00
	10	1.00	1.00	1.00	0.98	0.99	0.98
	20	1.02	1.00	1.02	0.98	0.98	0.98
	30	1.04	1.01	1.02	0.98	0.97	0.97
	40	1.07	1.04	1.05	1.00	0.99	0.98
	50	1.13	1.08	1.08	1.05	1.03	0.99
	60	1.19	1.12	1.13	1.11	1.09	1.03
	70	1.24	1.17	1.18	1.16	1.15	1.08
	80	1.27	1.22	1.23	1.20	1.20	1.13
20%	90	1.32	1.28	1.28	1.28	1.26	1.18
	100	1.38	1.30	1.30	1.33	1.33	1.21
	125	1.44	1.42	1.43	1.44	1.45	1.34
	150	1.58	1.48	1.53	1.57	1.60	1.44
	175	1.66	1.60	1.66	1.71	1.73	1.58
	200	1.78	1.70	1.73	1.87	1.85	1.67
	250	1.98	1.91	1.94	2.16	2.14	1.93
	300	2.25	2.12	2.19	2.45	2.44	2.20
	350	2.46	2.32	2.37	2.74	2.74	2.43
	400	2.64	2.56	2.62	2.96	2.99	2.70
	500	3.12	2.95	3.03	3.53	3.54	3.14
	0	1.00	1.00	1.00	1.00	1.00	1.00
	10	1.01	1.00	1.00	0.99	0.99	0.99
	20	1.05	1.02	1.01	1.00	0.99	0.98
	30	1.10	1.05	1.04	1.04	1.01	0.98
50%	40	1.18	1.09	1.07	1.09	1.06	0.99
	50	1.25	1.15	1.12	1.17	1.14	1.01
	60	1.29	1.19	1.18	1.22	1.20	1.04
	70	1.36	1.27	1.23	1.27	1.29	1.08
	80	1.39	1.28	1.29	1.33	1.35	1.12

	90	1.45	1.32	1.35	1.41	1.40	1.17
	100	1.49	1.38	1.38	1.47	1.47	1.23
	125	1.63	1.47	1.49	1.63	1.64	1.32
	150	1.69	1.59	1.60	1.80	1.80	1.42
	175	1.84	1.70	1.69	1.95	1.97	1.52
	200	1.91	1.81	1.84	2.11	2.15	1.65
	250	2.21	1.99	2.07	2.47	2.48	1.88
	300	2.43	2.27	2.26	2.77	2.84	2.10
	350	2.66	2.49	2.53	3.09	3.17	2.36
	400	2.94	2.74	2.73	3.44	3.50	2.59
	500	3.38	3.14	3.14	4.04	4.21	3.03

Land Use Changes (in 1000 acres)

Yield Increase	Carbon Price in $/MgCE	Arable Cropland			Afforested Land			Energy Crop Plantations			Total		
		Yield Increase assumed for:											
		All Crops	Energy Crops	Annual Crops	All Crops	Energy Crops	Annual Crops	All Crops	Energy Crops	Annual Crops	All Crops	Energy Crops	Annual Crops
0%	0	319973	319973	319973	0	0	0	0	0	0	319973	319973	319973
	10	324388	324388	324388	0	0	0	0	0	0	324388	324388	324388
	20	328396	328396	328396	2583	2583	2583	0	0	0	330979	330979	330979
	30	330958	330958	330958	2583	2583	2583	1	1	1	333541	333541	333541
	40	331555	331555	331555	2583	2583	2583	37	37	37	334174	334174	334174
	50	327008	327008	327008	2583	2583	2583	4926	4926	4926	334516	334516	334516
	60	321075	321075	321075	3532	3532	3532	14045	14045	14045	338652	338652	338652
	70	314397	314397	314397	3532	3532	3532	22820	22820	22820	340749	340749	340749
	80	305910	305910	305910	4673	4673	4673	34039	34039	34039	344622	344622	344622
	90	298807	298807	298807	8520	8520	8520	41668	41668	41668	348995	348995	348995
	100	292566	292566	292566	8647	8647	8647	48624	48624	48624	349838	349838	349838
	125	280539	280539	280539	9755	9755	9755	65466	65466	65466	355760	355760	355760
	150	268200	268200	268200	9755	9755	9755	78540	78540	78540	356496	356496	356496
	175	259873	259873	259873	9755	9755	9755	88254	88254	88254	357883	357883	357883
	200	252005	252005	252005	9755	9755	9755	96033	96033	96033	357794	357794	357794
	250	245003	245003	245003	9755	9755	9755	102466	102466	102466	357225	357225	357225
	300	238692	238692	238692	9755	9755	9755	107783	107783	107783	356231	356231	356231
	350	234900	234900	234900	9755	9755	9755	112513	112513	112513	357168	357168	357168
	400	229446	229446	229446	9755	9755	9755	118643	118643	118643	357844	357844	357844
	500	222595	222595	222595	9755	9755	9755	123793	123793	123793	356144	356144	356144
1%	0	318765	319973	318765	0	0	0	0	0	0	318765	319973	318765

	10	324053	324388	324053	0	0	0	0	0	0	324053	324388	324053
	20	327803	328396	327803	2583	2583	2583	0	0	0	330386	330979	330386
	30	331003	330958	331003	2583	2583	2583	1	1	1	333587	333541	333587
	40	331746	331555	331746	2583	2583	2583	37	37	37	334365	334174	334365
	50	326399	326948	326372	2583	2583	2583	5286	5155	5141	334268	334686	334096
	60	319413	320904	319801	3532	3532	3532	15040	14588	14521	337985	339024	337854
	70	313548	313973	313991	3532	3532	3532	24160	23447	23102	341240	340952	340624
	80	304621	305465	305019	4440	4612	4427	35549	34860	34632	344609	344937	344078
	90	297080	298238	297504	8502	8324	8487	43303	42552	42649	348885	349114	348640
	100	291678	292290	291849	8647	8647	8647	49505	49092	49017	349830	350030	349514
	125	277569	278707	280726	9755	9755	9755	68488	67294	65098	355813	355757	355580
	150	266391	266550	266830	9755	9755	9755	80288	80203	79765	356434	356508	356351
	175	257822	258795	258744	9755	9755	9755	90252	89608	89359	357830	358159	357859
	200	250760	251692	251676	9755	9755	9755	97153	96394	96102	357668	357842	357533
	250	243335	244902	243565	9755	9755	9755	103875	102788	103625	356965	357446	356946
	300	237046	238582	237214	9755	9755	9755	108896	107886	108727	355697	356223	355696
	350	233276	234617	233102	9755	9755	9755	114058	112876	113230	357090	357248	356088
	400	228550	229344	228712	9755	9755	9755	119833	118780	119564	358138	357880	358032
	500	221222	222547	220549	9755	9755	9755	124925	124073	124586	355903	356376	354891
	0	318135	319973	318135	0	0	0	0	0	0	318135	319973	318135
	10	323588	324388	323588	0	0	0	0	0	0	323588	324388	323588
	20	327234	328396	327234	2583	2583	2583	0	0	0	329816	330979	329816
	30	330801	330958	330801	2583	2583	2583	1	1	1	333384	333541	333384
	40	332261	331525	332261	2583	2583	2583	41	41	41	334884	334148	334884
2%	50	326204	326999	326167	2583	2583	2583	5601	5569	5023	334387	335150	333773
	60	317708	320481	318724	3532	3532	3532	16331	15169	14785	337571	339182	337041
	70	312140	314089	312948	3532	3532	3532	24726	24119	23600	340398	341740	340080
	80	302579	305091	304192	3847	4666	4442	37606	35500	34663	344032	345256	343298
	90	295055	297620	296401	8517	8236	8515	45247	43341	43568	348819	349197	348484
	100	289892	292029	290889	8647	8647	8647	51330	49452	49471	349869	350129	349007
	125	275477	276315	279087	9755	9755	9755	70387	69962	66391	355619	356032	355234

	150	264681	266068	265314	9755	9755	9755	81996	80871	81134	356432	356695	356203
	175	256261	257979	257333	9755	9755	9755	91806	90429	90706	357823	358164	357794
	200	249186	251387	251471	9755	9755	9755	98612	96705	96300	357554	357847	357526
	250	241582	244770	241840	9755	9755	9755	105221	102928	104934	356558	357453	356529
	300	235790	238469	235961	9755	9755	9755	109769	108084	109366	355314	356309	355082
	350	231610	234814	231480	9755	9755	9755	116115	114106	114463	357480	358676	355698
	400	226439	229517	226884	9755	9755	9755	121134	118933	120537	357329	358205	357176
	500	219557	222681	219238	9755	9755	9755	125925	124253	125496	355237	356690	354489
	0	316170	319973	316170	0	0	0	0	0	0	316170	319973	316170
	10	321602	324388	321602	0	0	0	0	0	0	321602	324388	321602
	20	327842	328396	327842	2583	2583	2583	0	0	0	330424	330979	330424
	30	330359	330958	330395	2583	2583	2583	37	1	1	332979	333541	332979
	40	330534	331525	331233	2583	2583	2583	1107	41	41	334223	334148	333857
	50	325800	326954	329172	2583	2583	2583	5973	5870	3761	334355	335406	335516
	60	313249	319163	316308	3532	3188	3532	19846	17060	15762	336626	339411	335602
	70	307127	312188	310253	3532	3532	3532	29402	26317	25479	340060	342037	339264
	80	296607	301432	301848	3647	3911	3807	43708	40716	35755	343962	346058	341409
5%	90	291360	295294	293131	8238	7567	8468	48906	46407	45773	348503	349268	347371
	100	286766	289661	288456	8647	8647	8647	54712	52375	51368	350126	350684	348471
	125	272474	274919	274563	9755	9755	9755	73144	71581	70677	355373	356255	354996
	150	259803	264835	263458	9755	9755	9755	86981	82919	83078	356540	357510	356291
	175	251598	256324	254438	9755	9755	9755	96454	92111	93534	357808	358191	357728
	200	247180	249878	248788	9755	9755	9755	100597	98339	98799	357532	357972	357342
	250	237008	244575	236940	9755	9755	9755	109224	103336	108045	355987	357667	354740
	300	230568	238604	231587	9755	9755	9755	114359	108744	111883	354683	357103	353225
	350	227206	233968	226737	9755	9755	9755	120449	115281	116672	357410	359004	353164
	400	222494	228882	221634	9755	9755	9755	124699	119985	122513	356948	358623	353902
	500	215384	222543	214925	9755	9755	9755	129179	124894	128364	354318	357192	353044
	0	317009	319973	317009	0	0	0	0	0	0	317009	319973	317009
10%	10	322045	324388	322045	0	0	0	0	0	0	322045	324388	322045
	20	327393	328396	327393	2583	2583	2583	0	0	0	329976	330979	329976

	30	327923	330901	328054	2583	2583	2583	247	37	36	330753	333521	330673
	40	327201	330016	327433	2583	2583	2583	1815	1774	466	331598	334372	330481
	50	317836	324416	326061	2583	2583	2583	15591	9881	4568	336009	336879	333211
	60	308501	315667	314695	3177	3200	3532	26508	22738	16694	338186	341605	334920
	70	298523	307067	305502	3532	3532	3532	39444	33117	27199	341498	343716	336232
	80	291870	298417	297958	3532	3532	3889	49048	44901	37930	344450	346849	339778
	90	285693	292603	289262	8499	6480	8647	55041	49980	48412	349233	349063	346321
	100	279239	286673	284971	8647	8647	8647	62122	56694	53798	350009	352014	347416
	125	266071	271317	271354	9755	9755	9755	79261	75808	72185	355087	356881	353294
	150	252051	261370	257941	9755	9755	9755	94278	87173	85395	356085	358298	353092
	175	246273	252876	246293	9755	9755	9755	101083	95592	97712	357112	358224	353761
	200	240369	248926	242690	9755	9755	9755	106083	99602	101853	356207	358283	354298
	250	228416	243726	228873	9755	9755	9755	115792	105320	112814	353964	358802	351443
	300	223938	238538	224304	9755	9755	9755	121693	111538	116722	355386	359832	350781
	350	220014	232545	219487	9755	9755	9755	125544	117035	121145	355313	359335	350387
	400	215798	227722	214151	9755	9755	9755	129920	121593	125834	355474	359071	349740
	500	209505	222362	210160	9755	9755	9755	134502	126708	131856	353762	358825	351771
	0	312778	319973	312778	0	0	0	0	0	0	312778	319973	312778
	10	314848	324388	314848	0	0	0	0	0	0	314848	324388	314848
	20	317085	328396	317076	2583	2583	2583	407	1	0	320075	330979	319658
	30	319786	330601	321098	2583	2583	2583	1792	231	191	324161	333415	323872
	40	315895	327173	321459	2583	2583	2583	12101	5295	1575	330578	335050	325617
	50	305082	316207	319229	2583	2583	2583	27208	20457	5245	334873	339247	327057
20%	60	293327	309172	309991	2717	2604	3532	42257	30547	17352	338301	342323	330875
	70	286965	298989	297864	3364	3532	3532	52221	43085	30889	342550	345605	332284
	80	281997	293094	287658	3532	3532	4533	58307	50940	45392	343836	347566	337583
	90	273918	286103	284595	8479	6443	8647	68985	57660	51344	351382	350206	344586
	100	265697	277138	281405	8647	8282	9047	76577	69066	55780	350921	354486	346231
	125	251715	266340	264393	9755	9755	9755	91509	81481	74274	352979	357576	348422
	150	238715	256434	249655	9755	9755	9755	103736	92799	88744	352206	358989	348154
	175	230168	250079	240314	9755	9755	9755	114028	98793	99529	353952	358628	349599

	200	224051	247425	230185	9755	9755	9755	119210	102250	108428	353017	359431	348368
	250	214865	242406	218289	9755	9755	9755	128018	108737	119176	352639	360899	347220
	300	211800	234245	210740	9755	9755	9755	130032	116432	125516	351587	360432	346012
	350	207620	228861	206325	9755	9755	9755	134676	120880	129570	352051	359497	345650
	400	203003	226734	202538	9755	9755	9755	137940	123471	132975	350698	359961	345269
	500	199906	221495	198691	9755	9755	11562	143332	128421	135253	352993	359672	345507
	0	292761	319973	292761	0	0	0	0	0	0	292761	319973	292761
	10	293442	324390	293878	0	0	0	2564	1	0	296007	324391	293878
	20	293462	327364	294689	2583	2583	2583	7275	1112	1110	303319	331059	298381
	30	285398	321409	294906	2583	2583	2583	26923	14491	2320	314903	338482	299809
	40	274952	310382	292120	2583	2583	2583	43997	28288	4742	321532	341253	299445
	50	264755	299068	289814	2583	2583	2583	61349	42831	13893	328687	344482	306290
	60	256444	292479	281112	2583	2583	3532	73987	53613	26610	333014	348674	311254
	70	251378	282164	272824	2583	2638	3532	80024	66033	40875	333985	350835	317231
	80	241941	273071	269104	3205	3218	6376	90840	76492	50590	335986	352781	326070
50%	90	234265	268354	263587	6371	4427	8647	98701	82558	57852	339336	355339	330087
	100	228299	264914	255302	8203	6458	9165	104779	86680	68843	341282	358052	333310
	125	215367	251780	243721	9755	9755	9755	119970	98955	82313	345092	360490	335789
	150	206875	249236	232665	9755	9755	9755	130901	102492	97426	347531	361483	339846
	175	200269	243568	223716	9755	9755	9755	137466	108256	107799	347490	361580	341271
	200	197515	236992	214828	9755	9755	9755	142961	114950	117018	350232	361697	341601
	250	189693	230885	198071	9755	9755	9755	149513	121077	135314	348962	361718	343141
	300	186784	228830	190772	9755	9755	9755	152885	123212	140470	349425	361797	340997
	350	183625	224810	184329	9755	9755	9755	156435	127054	146187	349816	361620	340271
	400	182199	222743	179709	9755	9755	9755	158871	129147	150610	350824	361646	340075
	500	177574	219507	173732	9755	9755	12848	161073	132564	152906	348402	361827	339485

III.5. SBA DISASTERS by GEO-BENE Consortium Partners

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Interim Report **IR-08-048**

Banda Aceh—The Value of Earth Observation Data in Disaster Recovery and Reconstruction: A Case Study

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Contents

Abstract

On 26 December 2004, Banda Aceh in Indonesia was at the center of one of the worst natural disasters to affect mankind. Large amounts of international aid poured in to assist in the relief and reconstruction efforts. Amongst this effort, were investments in basic earth observation data from in-situ, airborne and space observations. While the use of this data is assumed to be crucial, few efforts have gone into quantifying the benefits of its acquisition.

The objectives of this study were to interview a cross-section of agencies operating in Banda Aceh and across the province of Nanggroe Aceh Darussalam on the use, sources and quality of earth observation data in the relief/reconstruction effort; and to analyze and quantify the value that earth observation data brings to the relief/reconstruction effort based on the survey results and specific examples.

Key findings from the interviews point to an overall improvement in the spatial data situation since the tsunami. Problems identified included insufficient training, lack of timely data and sometimes poor spatial resolution. Specific examples of the cost-benefits of earth observation data were typically on the order of millions of dollars and involved large time savings.

IIASA is one of 12 partners in the European Union sponsored project "Global Earth Observation—Benefit Estimation: Now, Next and Emerging" (GEO-BENE). Additional GEO-BENE partner countries include Germany, Switzerland, Slovakia, Netherlands, Finland, South Africa and Japan. Within GEO-BENE we are developing methodologies and analytical tools to assess societal benefits of GEO in nine societal benefit areas—one of which is disasters. The tsunami affected province of Nanggroe Aceh Darussalam, and specifically Banda Aceh, has been selected as a case study. Other case studies representing different societal benefit areas include: biodiversity in South Africa, health and climate in Finland, fire in Europe, etc. For more information please refer to: www.geo-bene.eu.

Acknowledgments

Our thanks go to M. Yakob Ishadamy and colleagues of the Spatial Information and Mapping Centre of the Badan Rehabilitasi dan Rekonstrucksi, Nanggroe Aceh Darussalam, Nias and Muzailin Affan and colleagues of the Remote Sensing and Geographic Information System Centre in Syiah-Kuala University who hosted the case study and provided logistical support.

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The authors would sincerely like to thank everyone who took time from their busy schedules working on their post tsunami reconstruction activities in Banda Aceh to participate in the interviews (see Table 1) and those who provided further details for case studies (see Table 2).

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Banda Aceh—The Value of Earth Observation Data in Disaster Recovery and Reconstruction: A Case Study

Ian McCallum, Richard Kidd, Steffen Fritz, Florian Kraxner, and Michael Obersteiner

1 Introduction

On 26 December 2004, Banda Aceh in Indonesia was the scene of one of the worst natural disasters to affect mankind. Because of the extreme nature of the event, large amounts of funding and support were provided on an unprecedented level. According to the RAN (Recovery Aceh – Nias) Database (http://www.rand.brr.go.id/RAND/), as of 10 January 2008 a total of 490 agencies have committed 3.8 billion United States Dollars (USD). Among this vast amount of support are various types of earth observation data (i.e., orthophotos, satellite scenes and the creation of a group—Spatial Information and Mapping Centre (SIM-Centre) to administer this data). It is crucial for the efficient use of the emergency aid funding as well as for the following reconstruction of the infrastructure (roads, harbors, bridges, etc.) that up-to-date geographical information is collected and creates the base for planning the aid program (BlomInfo, 2006).

The use of earth observation data in the area of disaster recovery has been identified as a necessary and indispensable tool. The international charter *Space and Major Disasters* came into effect in 2000 to coordinate space data acquisition and delivery to those affected by natural or technological disasters. Quantifying the benefit of this technology is, however, another matter and remains largely unexplored. Theoretical descriptions include work by Bounfour and Lambin (1999) and Macauley (2006), with PWC (2006) producing a quantitative assessment; however these stop short of offering easily applicable methodologies. Costs are deemed necessary and benefits assumed plenty in this relatively young field of technology, where costs are enormous but dispersed, often shared by governments, private industry and end users.

Within the Global Earth Observation System of Systems (GEOSS), the European Union (EU) funded project Global Earth Observation Benefit Estimation (GEO-BENE; http://www.geo-bene.eu) is charged with estimating cost-benefits of earth observation data for nine societal benefit areas. One of these areas is titled *reducing loss of life and property from natural and human-induced disasters* (GEOSS, 2005). In an effort to better understand the benefits associated with using earth observation data in disaster regions, Banda Aceh, Indonesia was selected as a case study within the EU funded project GEO-BENE.

The objectives of this study were to:

1. interview a cross section of agencies operating in Banda Aceh and across the province of Nanggroe Aceh Darussalam (NAD) on the use, sources and quality of earth observation data in the relief/reconstruction effort, and
2. analyze and quantify the value that earth observation data brings to the relief/reconstruction effort based on the survey results and specific examples.

2 Methodology

In order to capture the varying information available in such a study (data ranging from qualitative to quantitative), various methods have to be used. Unfortunately among the literature, methodologies are lacking which could be applied in the cost-benefit assessment of earth observation data in this context. This study employs a two-step approach: (1) design, implement and analyze a questionnaire; and (2) collect and analyze specific cost-benefit examples.

2.1 Questionnaire

With the help of local partners in Banda Aceh, the SIM-Centre of the Badan Rehabilitasi dan Rekonstruksi (BRR; Agency for Reconstruction and Rehabilitation of NAD and Nias), and the remote sensing and Geographic Information System (GIS) Centre at Syiah-Kuala University (UNSYIAH), a list of 18 groups working in Banda Aceh and using earth observation data was created (see Table 1). This included groups representing national government (2), local government (2), universities (3), the United Nations (UN; 3) and non-governmental organizations (NGOs; 8). In addition, groups and projects using earth observation data were identified using the RAN database),[1] but were not included in this study.[2]

Following this, a questionnaire was designed to be given to each of these groups (see Appendix I). The questionnaire was designed so that it would be applicable to the wide range of groups being visited, easy to translate if required, and quick to complete. The advantage of this approach was that it allowed interviews across a broad cross section of earth observation users; the disadvantage being that results are rather general and sample sizes small.

With groups identified and the questionnaire designed, a field visit was made to Banda Aceh, Indonesia between 4 and 12 December 2007. Each of the groups listed in Table 1 were visited and a short interview was conducted, lasting between 30 to 60 minutes. The questionnaire was used as a basis for the interview. Results from the questionnaire were then compiled for analysis (see Appendix II).

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[1] URL last visited on 27 October 2008.

[2] A query of the RAN datasets on 10 January 2008 under the sector *spatial planning and environmental protection* revealed a total of 47 organizations listed with a combined total of 101 million USD committed to the relief effort.

Table 1: Organizations visited in Banda Aceh, Indonesia.

Organization Type	Organization	Contact
National Government	BRR, Pusdatin	Mr. E. Darajat
National Government	BRR, Bakosurtanal[a]	Mr. Darmawan
University	UNSYIAH (GIS and Remote Sensing —RS)	Mr. M. Affan
University	UNSYIAH, Vice Rector	Mr. Dhalan
University	UNSYIAH, TDMRC[b]	Mr. Dirhamsyah
Local Government	BPN[c]	Mr. G. Suprato
Local Government	AGDC[d]	Mr. S. Gan
UN	UN ORC[e]	Mr. H. Busa
UN	UNICEF	Mr. B. Cahyanto
UN	FAO	Mr. Sugianto
NGO	LOGICA[f]	Mr. D. Hurst
NGO	GTZ-SLGSR[g]	Mr. M. Widodo
NGO	ManGEONAD[h]	Mr. T. Rehman
NGO	Leuser International Foundation (YLI)	Ms. D.R. Sari
NGO	Flora Fauna International (FFI)	Mr. Syaifuddin
NGO	ABD-ETESP[i]	Mr. E. Van Der Zee
NGO	Sea Defence Consultants	Mr. J. Kraaij
NGO	Sogreah	Mr. B. Coiron

[a] Badan Koordinasi Survei dan Pemetaan Nasional (National Coordinating Agency for Surveys and Mapping); [b] Tsunami and Disaster Mitigation Research Centre; [c] Aceh Province Land Agency; [d] Aceh Geospatial Data Centre; [e] Office of the United Nations Recovery Coordinator for Aceh and Nias; [f] Local Governance and Infrastructure for Communities in Aceh; [g] Support for Local Governance for Sustainable Reconstruction; [h] Management of Georisk Nanggroe Aceh Darussalam; [i] Asian Development Bank, Earthquake and Tsunami Emergency Support Program.

2.2 Cost-benefit Examples

Several groups were identified from both the interviews and discussions that could provide specific quantitative examples of the value of using earth observation data (see Table 2). These groups were then contacted by email and asked to provide the necessary data to make such comparisons. These examples were analyzed using cost-benefit comparisons where possible and are presented in Section 3.2. Full contact details for the technical experts who provided the responses are provided in Appendix III.

Table 2: Description of quantitative benefit estimation examples in Banda Aceh, Indonesia.

No.	Organization	Contact	Cost-Benefit Example	Report Section
1	USGS[a]	C. Wilson	Cost-benefit of global positioning system (GPS) for community based bathymetric mapping	3.2.1
2	CRS-ITB[b]	K. Wikantika	Comparison of traditional surveying to orthophotos	3.2.2
3	Logica	D. Mate	Use of orthophotos for community based mapping and survey	3.2.3
4	Sogreah	B. Coiron	Banda Aceh water strategy 2007–2030 and short-term action plan	3.2.4
5	Sim-Centre	R. Kidd	Digital orthophoto cost-benefit	3.2.5

[a] United States Geological Service; [b] Centre for Remote Sensing, Institute of Technology Bandung.

3 Results

In total, 18 organizations were interviewed over the course of four days with over 40 people participating in the interviews. Interviews ranged from brief discussions with the aid of an interpreter, to detailed presentations. In addition, various discussions were held with supervisors and administrators which added to the overall impression.

3.1 Questionnaire

Results from the questionnaire are summarized in Appendix II. Several questions in the survey were answered similarly by all groups and were not summarized. In addition, three of the questionnaires were withdrawn from the analysis owing to lack of information. Questions were very general and the group rather diverse, thus the answers are also rather general. However, some clear trends appear and certain individuals provided additional details.

At this point it is clear that most, if not all, participants believe a substantial improvement has occurred in terms of spatial data between the time of the tsunami and the time of the interview (see, Figure 1). Of the 15 respondents, 13 indicated at least an improvement of one category (i.e., a shift from poor to satisfactory, or from satisfactory to good). Associated with this general improvement is a large expenditure—the difficulty arises in attempting to associate a cost-benefit to this.

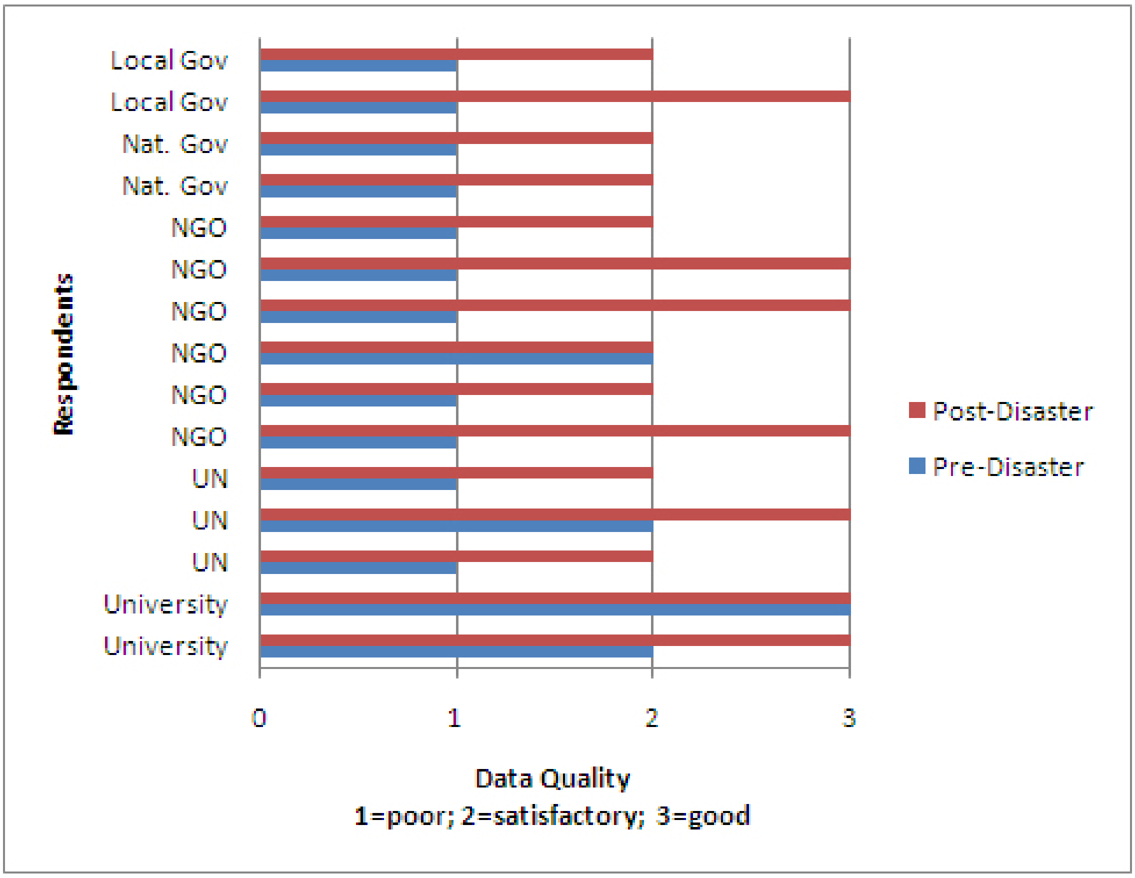

Figure 1: Perception among interviewees on the improvement of earth observation data in the region.

Training is another theme that most respondents agree upon—there needs to be more across all groups. Over half of all respondents indicated the lack of training as hindering their activity. All groups questioned were aware of this issue and were taking various steps to address it, however it remains unsolved. This will likely become problematic as various foreign aid groups leave and data, etc., is passed over to local and national governments.

Finally, the major desire in terms of data improvement among the participants seems to be a faster response time—people need more timely datasets and, in many cases, they are not receiving them. In particular, disaster regions are typified by rapid change. In fields such as reconstruction, groups require accurate and updated data. A lack of this data translates into more hours of field work, greater expenses and delays. This is, however, difficult to quantify based on the results from this questionnaire.

3.2 Cost-benefit Examples

The purpose of the questionnaire was to identify general trends among the earth observation data users in Aceh. In an effort to determine cost-benefit, several examples were identified (see Table 2) from among the groups interviewed. The technologies employed ranged from GPS to aerial photography and digital orthophotos.

3.2.1 Cost-benefit of GPS for Community Based Bathymetric Mapping

Since 1 June 2007, a pilot project has been established in Aceh enabling fishing communities to collect bathymetric data. The primary threat to the majority of fishermen is the lack of documented and accurate information about the location of underwater hazards (Wilson *et al.*, 2007). Relatively inexpensive GPS technology is being employed to fulfill this task and, when compared to the avoided costs, results in substantial savings to the fishermen (see Table 3). In particular, damaging a fishing net amounts to 4,000 USD (its loss would cost 20,000 USD) with damage typically happening twice per year (Wilson, 2007). As of 31 March 2008, none of the five boats taking part in the study had damaged their nets (Wilson, 2008), suggesting that the GPS units are having an effect. In addition, the collected information is used to chart the local knowledge of sea mounts, deep reefs, hazards to fishing gear operation, and fishing resources in the region (Wilson *et al*., 2007).

Initial results from the project (Wilson, 2007) have already demonstrated a clear change in pre and post tsunami bathymetry near the main river mouth (Krung Aceh) serving Banda Aceh's main fishing port, cargo and ferry terminals. The port is also the main commercial port for the whole province. Figure 2 shows depth derived from sounding data collected by the fishing communities compared to pre-tsunami national bathymetric data and clearly shows a silting up of the main port entry channel. The benefit associated in providing new information on the status, depth and route of the port entry channel has not been measured. Since April 2008, the project has been expanded to two further port locations in NAD and now includes a further 55 boats.

Table 3: Annual cost-benefit of GPS for sea fishing. Source: Wilson (2007).

Description (USD/year)	Costs of Technology	Avoided Costs	Cost Benefit
Cost-benefit of GPS for sea fishing (5 boats) [a]	4,650	40,000	35,350
Cost-benefit of GPS for boat safety[b]	930	60,000	59,070

[a] Per boat costs of technology: GPS unit 750; installation 30; 3 hours training 150; total costs = 930. Avoided costs per boat refer to: lost income for 1 week of net repair 3000; cost of new repair 1000; total cost of net repair is 4000—on average this occurs twice a year.

[b] This describes one incident where a boat suffered engine damage in a storm and was rescued before sinking because both it and the rescue boats were equipped with GPS units and were able to quickly locate its whereabouts. Avoided costs include only the boat and net and make no attempt to place value on the lives of the 18 fishermen on board. (Also reported on http://www.acehfisheries.org/modules/news/article.php?storyid=18; URL verified on 29 October 2008.)

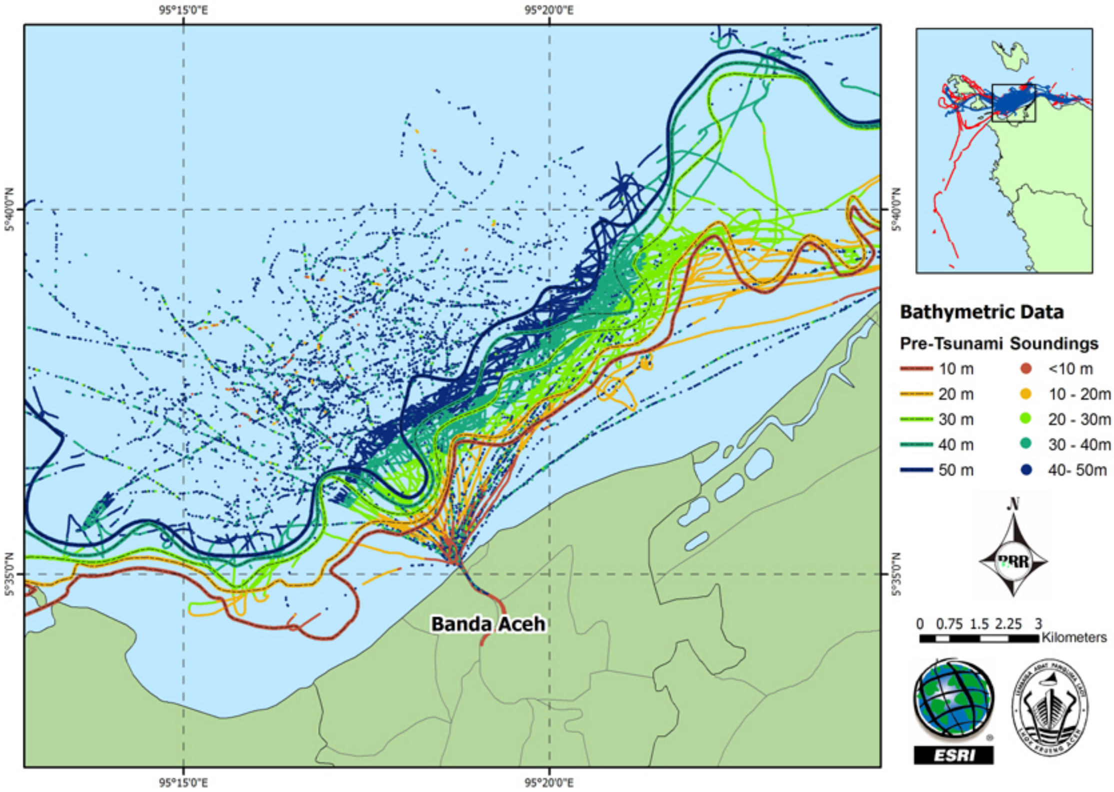

Figure 2: Comparison of pre-tsunami (lines) bathymetric and post tsunami (points) sounding data.

3.2.2 Comparison of Traditional Surveying to Orthophotos

A simple example cost comparison is made here between terrestrial mapping versus aerial photogrammetry (see Table 4) to cover the approximate 1,000 square kilometer (sq. km) tsunami affected area in the province of NAD. The cost calculations are estimated based on 50 centimeters (cm) digital aerial photogrammetry, assume the availability of a reasonable resolution Digital Elevation Model (DEM), and are compared to the effort involved to complete a traditional 1:10,000 scale geodetic survey.

Table 4: Comparison of traditional surveying to orthophotos at scales better than 1:10,000, or 50 cm resolution aerial photography. Source: Wikantika (2008).

	Terrestrial Mapping	**Aerial Photogrammetry (Digital)**
Cost	100 USD/hectare (ha)	12–14 USD/ha
Manpower	5 ha/day/team	50,000 ha/year/company
Damaged Area	100,000 ha	100,000 ha
Time	1 team = 55 years	1 company = 2 years
	1000 teams = 6 weeks	10 companies = 2.4 months
Total Cost	***8.76 million USD***	***1.2 million USD***

It is clear from this comparison that aerial photography offers large cost savings over the traditional approach. Additional benefits also accrue: namely a digital product, a uniform and consistent approach to mapping, and likely faster results. It is assumed that use of satellite products would see further cost reductions however any cost savings would have to be weighed against classification quality.

3.2.3 Use of Orthophotos for Community Based Mapping and Survey

The Australia-Indonesia Partnership for Reconstruction and Development (AIPRD) administered the Local Governance and Infrastructure for Communities in Aceh (LOGICA) program as part of the Australian government's response to the tsunami.

One of the four components of the LOGICA program was to re-establish land ownership. A large part of this was achieved through a series of community based mapping (CBM) projects in collaboration with villagers in the 600 affected communities. The CBM projects resulted in community agreements on land ownership which were documented as simple community maps.

A further action, initiated via LOGICA's Community Housing Assistance Monitoring Program (CHAMP) lead to the conversion (rectification) of the schematically correct community maps into georeferenced maps (corrected cartographic products) at 1:1,500 scale using GIS tools and available high resolution orthorectified aerial photography. An example of the stages of this process is shown in Figure 3. CHAMP also acquired detailed survey information in 203 of the affected communities concerning the status of housing construction. Integrating both the georeferenced maps and survey data in a single GIS provided a tool to allow for spatial planning at the district and provincial levels.

A comparison, in terms of effort, for the acquisition of the information to allow for the creation of this tool via traditional survey methods and via the use of earth observation and GIS techniques can be made.

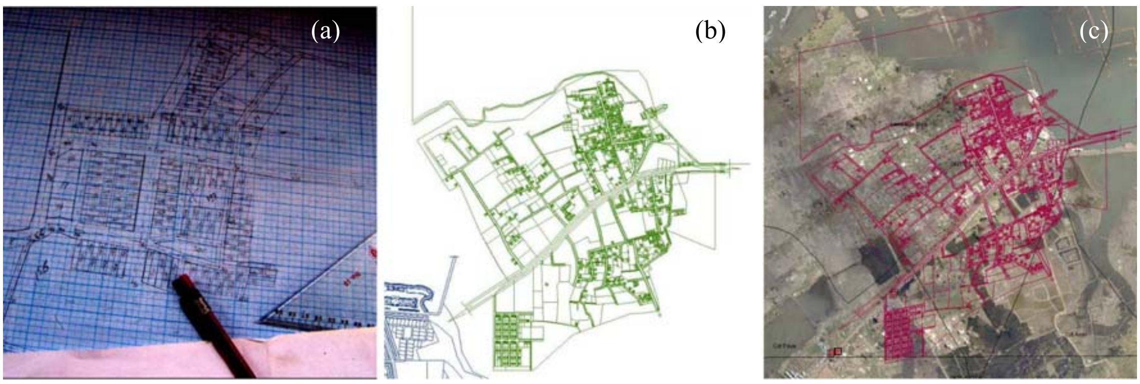

Figure 3: (a) Creation of a simple community based land ownership map (part of); (b) CBM converted to AutoCAD to record land ownership agreement and details; (c) CBM rectified using orthorectified aerial photography.

Traditional Survey:

- Capture and collation of spatial data per community = 3 persons for 1 month;
- Total effort for 600 communities = 1,800 months.

Earth Observation and GIS:

- Capture (digitization), rectification of earth observation derived spatial data, integration of attribute data = 8 persons for 7 months;
- Total effort for 600 communities: 48 months.

In the scope of this project, traditional survey methods are seen to require 36 times more effort to provide the same information.

3.2.4 Banda Aceh Water Strategy 2007–2030 and Short-term Action Plan

The Aceh and Nias Post Tsunami and Earthquake Reconstruction Program (ANTERP) implemented by Sogreah in collaboration with Banda Aceh City Water Utility (PDAM) initially provided engineering design drawings for new roads and drainage to the BRR for prioritization and coordination of reconstruction activities and further provided the BRR with maps comparing construction progress of housing and roads before and after 2007 across the city of Banda Aceh.

The project made use of high resolution, 25 cm, orthorectified aerial imagery acquired in June 2005, available at a scale of 1:2,000 provided at no cost through the SIM-Centre of the BRR. The imagery was used to assess the damage to the piped water and drainage system in Banda Aceh and further to provide city mapping and then to plan engineering designs for new piping networks for the PDAM.

An assessment of construction progress for housing and roads across Banda Aceh city was implemented in November 2007 by a comparison of the city mapping and high resolution Kompsat Imagery (1 meter—m) acquired in May 2007. The imagery was provided at no cost to the program through the SIM-Centre. An example product showing the reconstruction progress of one of the most devastated villages (Ulee Lheue) is given in Figure 4. Reconstruction activities are shown in green.

It is estimated that the information derived from both image sets to support both projects would have cost approximately 100,000 USD to obtain from traditional sources.

A comparison of costs for production of progress mapping (2005–2007) can be provided by considering the effort required to create the map across the sub district Meuraxa in Banda Aceh. The Meuraxa sub district (yellow in inset in Figure 4) has a survey area of 7.5 sq. km.

Figure 4: Ulee Lheue village buildings and roads comparison 2005–2007; KOMPSAT satellite imagery of Banda Aceh (22 May 2007), city mapping derived from orthorectified aerial imagery (June 2005).

The cost effort to produce mapping from earth observation and GIS:

- Cost of orthophotos and GIS data showing infrastructure (building and road extent): no cost—donated by the Norwegian government (actual cost is 200 USD sq. km: total cost 1,500 USD).
- Cost of Kompsat Imagery: no cost—donated by Korean space agency (actual cost 14–19 USD sq. km: total cost[3] 105–143 USD).
- Time/Effort: 2 months.

Effort to produce mapping from traditional geodetic survey:

- Geodetic survey at 1:10,000 for a survey of 7.5 sq. km (750 ha), requires a total of 150 days effort for a survey team of three, equating to 20 months total effort for each survey. Two surveys would be required, one each in 2005 and 2007. Total effort = 40 months.

In terms of creating this product, use of traditional survey techniques requires 20 times more effort.

[3] Assuming minimum area coverage order requirements are met—currently 50 sq. km (SPOT IMAGE, 2008 pricing).

3.2.5 *Digital Orthophoto Cost-benefit*

In January 2005, at the request of the Indonesian government, the Norwegian Agency for International Development (NORAD) provided a grant for the creation of an orthophoto dataset covering more than 6350 sq. km of Acehnese coastal regions affected by the 2004 tsunami. It was seen as crucial for the efficient use of emergency aid funding, as well as for infrastructure reconstruction (roads, harbors, bridges, etc.) that up-to-date geographical information was collected to create the base for planning the aid program (BlomInfo, 2006). The project was carried out over the period March 2005 to June 2006. The total value of the project amounted to 1,432,994 Euros (€).

The digital orthophoto data set was created by BlomInfo (2006) and final delivery of the products was completed by May 2006 to the Indonesian National Coordinating Agency for Surveys and Mapping (Badan Koordinasi Survei dan Pemetaan Nasional—Bakosurtanal). In late August 2006, the digital orthophoto data set and GIS data was delivered by Bakosurtanal to the SIM-Centre of the BRR for dissemination to the aid and recovery community in NAD. The SIM-Centre and Bakosurtanal were the sole authorized distributors of the data sets, both of whom made the datasets available to the recovery community at no cost.

During the period August 2006 to August 2008, the SIM-Centre distributed the data to 79 users and Bakosurtanal to a further 18, totaling 99 users of the dataset in the recovery and rehabilitation process. In general, the users had sufficient capacity to work with this earth observation and GIS data set. The users came from all aspects of the recovery community and were seen to have the following distribution: national and local government (37%), NGO (28%), UN (14%), others (i.e., university or research groups, or undefined group association—8%), donor (7%), and international organizations (6%).

A detailed analysis of the data usage was initiated in July 2008, by survey of the technical experts who had used the data. The analysis found that over half of the survey respondents who used the orthophoto and GIS data (23 users) claimed that the data was critical to the successful implementation, operation and completion of their projects, and that without the data their projects would not run or be effective. The orthophoto and GIS data set critically supported by 28.4 million € worth of reconstruction projects, whilst further supported (i.e., data used, but not critical to project operation) by a total of 880.73 million € of reconstruction projects. It was further estimated that in order to obtain the same level of information by traditional means by those projects that deemed the data critical, it would have cost a minimum of 3.5 million €.

The majority of the data users (91%) employed the data set at the project planning phase (phase 2 of the normal 5 phase project cycle) and as such the main problem with the provision of the data set was the timeliness of its delivery into the aid and recovery community by Bakosurtanal.

A more detailed analysis of the cost-benefit of the use of the orthophotos provided by this project as well as a complete chronology of the project and related issues is provided in an upcoming report.

3.2.6 Summary of Cost-benefit Examples

In summary, all five of the cost-benefit examples examined in this study describe large cost and time savings with the use of earth observation data (see Table 5). Outstanding among these examples was the acquisition of digital orthophotos with an initial investment of 1.4 million €, which provided large benefits in terms of supporting other projects.

Table 5: Summary table of quantitative benefit estimation examples.

Organization	Example (Report Section)	Estimated Benefit
USGS	Cost-benefit of GPS for community based bathymetric mapping (3.2.1)	94,570 USD
CRS-ITB	Comparison of traditional surveying to orthophotos (3.2.2)	7.56 million USD
LOGICA	Use of orthophotos for community based mapping and survey (3.2.3)	36 fold savings
Sogreah	Banda Aceh water strategy 2007–2030 and short-term action plan (3.2.4)	20 fold savings
Sim-Centre	Digital orthophoto cost-benefit (3.2.5)	*Saved:* 2.1 million (m) € *Benefit (critical):* 28.4 m € *Benefit (supported):* 880.73 m €

4 Discussion

This study outlines the initial data collection and analysis attempting to describe the role that earth observation data plays in disaster relief and reconstruction efforts. The province of Aceh and the Nias Islands in Sumatra, Indonesia have been chosen as the case study region. After the tsunami on 26 December 2004, large amounts of relief effort poured into the affected regions and a necessary part of this relief effort involved earth observation data.

Initially, a questionnaire was designed along with interviews of key organizations in the region to better assess the use and benefits of earth observation data. Key findings from the questionnaire point to an improvement in the data situation since the tsunami, generally from poor to satisfactory or good. This has come about because of large amounts of money being spent in the form of basic data, training, data administration, etc. Problems identified include an insufficient level of staff training in the use of all earth observation related data, waiting too long to receive new data, and often insufficient data resolution. These problems are serious as trained staff is necessary, especially as foreign aid organizations leave the region. In addition, with such rapid change in an area under intensive reconstruction, new and updated information is crucial. Where necessary, this information must also meet spatial resolution requirements.

Further specific cost-benefit examples were provided from the region showing the growing use of earth observation data and the benefits accrued. Especially in post-disaster/reconstruction regions where timeliness is crucial, it appears that the benefits from the application of earth observation data are numerous. Cost-benefits identified in the various examples were typically in the order of millions of dollars, involving large time savings.

References

BlomInfo (2006). Creation of an Emergency GIS for the Rehabilitation and Reconstruction of Nanggroe Aceh Darussalam (NAD) and Northern Sumatra (SUMUT). BlomInfo A/S (GeoTech), Copenhagen, Denmark, 39 pp.

Bounfour, A. and E.F. Lambin (1999). How Valuable is Remotely Sensed Information? The Case of Tropical Deforestation Modeling. *Space Policy* **15**: 149–158.

GEOSS (2005). Global Earth Observation System of Systems (GEOSS): 10-year Implementation Plan Reference Document. GEO 1000R / ESA SP-1284 February, ESA Publications, Noordwijk, Netherlands, 209pp.

Macauley, M.K. (2006). The Value of Information: Measuring the Contribution of Space-derived Earth Science Data to Resource Management. *Space Policy* **22**: 274–282.

PWC (2006). Socioeconomic Benefits Analysis of Global Monitoring for Environment and Security (GMES). Main Report, PriceWaterhouseCoopers (PWC) prepared for the European Space Agency (ESA), ESA Contract 18868/05, 210 pp.

Wikantika, K. (2008). Personal communication.

Wilson, C. (2007). Personal communication.

Wilson, C. (2008). Personal communication.

Wilson, C., R. Kidd and Aliman (2007). Community-based Survey to Identify Position of Sea Mounts, Reefs and Other Fishing Locations. Map Asia, Paper Reference Number MA07 PN 227, 14–16 August, Kuala Lumpur, Malaysia.

Appendices

Appendix I: Earth Observation Questionnaire

GEOBENE

I I A S A

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The International Institute for Applied Systems Analysis (IIASA) is leading the European Union sponsored project "*Global Earth Observation—Benefit Estimation: Now, Next and Emerging*" (GEO-BENE). Within GEO-BENE we are developing methodologies and analytical tools to assess societal benefits of GEO in nine societal benefit areas—one of which is disasters. GEO in this sense refers to all forms of global earth observation—*in-situ*, maps, aerial photos, satellite data, etc.

The tsunami affected province of Nanggroe Aceh Darussalam (NAD), and specifically Banda Aceh, has been selected as a case study. In December 2007, the GEO-BENE project will be visiting Banda Aceh to collect information from users of GEO Data. Working with the SIM-Centre, BRR and the GIS and Remote Sensing Development Centre of UNSYIAH, GEO-BENE has identified your organization as a potential user of GEO data.

We would be very grateful if you could provide a response to the questions found in this questionnaire. (Estimated time to complete: 15 minutes). Your response will be used to generate statistical information about the use and need for GEO data in the response to a disaster, and will be reported upon in a scientific journal article. Please make sure to tick the box if you wish your project to be directly acknowledged in this article, and if you would like to receive a copy of the final article.

Organization Name: ____

Your Name: ____

Title: ____

Length of Employment: ____

Date: ____

Please acknowledge my project in your article ☐ **(Please tick)**

Please send me a copy of your final article ☐ **(Please tick)**

If you have ticked either of the above please provide e-mail address:

1 General Background

1.1 Is your organization currently using any form of GEO data? (Please circle)

- Surveys
- Maps
- Aerial photos
- Satellite data
- Other: ____

1.2 For what purposes are you using this GEO data? (Please circle)

- Health
- Housing and Settlement
- Education
- Governance
- Water/Sanitation
- Environmental
- Other: ____

1.3 From where have you obtained your GEO data? (Please circle)

- National Government (i.e., Bakosurtanal)
- Local Government (Bappeda)
- UN
- BRR
- Other: ____

1.4 Could you operate without this information? Yes / No

2 Baseline GEO Data

2.1 In your opinion, what was state of GEO information when the tsunami struck? (Poor, Satisfactory, Good) (Please circle)

2.2 What is the state of GEO information now? (Please circle) (Poor, Satisfactory, Good)

2.3 Do you believe that GEO data (maps, etc.) have helped thus far with the relief effort? Yes / No

3 Current/Future GEO Data

3.1 How do you expect investments in GEO information will help if another tsunami were to strike in this region? (Please rank)

- Saved lives
- Faster response
- Less damage
- Other: ____

3.2 Which improvement to GEO data would be most useful in your opinion? (Please rank)

- Higher resolution
- Better frequency
- More *in-situ*
- Timely delivery
- Improved access
- Other: ____

4 Resources and Capabilities

4.1 Do you and your group have the capacity (trained staff) and resources (hardware/software) to make use of improved information? Yes / No

4.2 In general, what is more important in your opinion:

- to improve information received, or
- to increase resources to work with information (i.e., training, hardware, software etc.)?

5 Specific Examples

5.1 Please identify specific examples of the areas in which you work that involve the use of ground data, aerial photos, satellite data, maps, etc. (Please circle)

- Tsunami warning
- Environmental monitoring
- Water quality
- Mangrove rehabilitation
- Housing construction
- Other: _______________________________________

5.2 How would you classify yourself in terms of your ability to answer the questionnaire?

(Familiar, Knowledgeable, Expert)

Thank you for taking the time to answer this questionnaire. If you have provided complete contact information on page one you will receive a copy of the results of this study once completed.

Appendix II: Summary of Questionnaire Results

1.1	1.2	1.3	2.1	2.2	3.1	3.2	4.1	4.2	5.1
All	Housing	UN	Poor	Satisfactory	Faster Response	Better Frequency	Yes	Training	Housing
All	Housing; Environmental	All	Poor	Satisfactory	Faster Response	Better Frequency	Yes	Training	Housing; Mangrove
All	Education; Environmental	All;JICA;LAPAN	Satisfactory	Good	Faster Response	Better Frequency	No	Training	All
All	Health; Education; Governance	All	Good	Good	Faster Response	Better Frequency	No	Training	All
All	Certification	BRR	Poor	Good	Problem Resolution	High Resolution	No	Training	Certification
All	All	Sim-C; BRR; JICA	Poor	Satisfactory		High Resolution			
All		Govt; BRR; SPOT	Poor	Good		Better Frequency; Access			
All						High Resolution	Yes		
Surveys; Maps	All	All	Poor	Satisfactory	Faster Response	Access			
All	All	BRR; Quickbird	Satisfactory	Good	Faster Response				
All	Forestry; Fisheries	BRR	Poor	Satisfactory		Better Frequency		Training	
Surveys	Housing	Surveys	Poor	Satisfactory		Better Frequency			
All	Environmental	All	Satisfactory	Satisfactory		Better Frequency		Training	
All	Housing	BRR; SPOT; Radarsat	Poor	Good	Faster Response	Better Frequency		Training	
All	Environmental								
Maps; Photos; Satellite	Environmental	BRR; ADB	Poor	Good		Better Frequency		Training	
All	Water	BRR; SPOT	Poor	Satisfactory		Better Frequency			

Note: Column headings refer to question number as provided in Appendix I; blank cells indicate no response.

Appendix III: Case Study Contact Details

Person/Position	Project/Agency	Contact Details
C. Wilson Project Director	Community Based Bathymetric Survey, Network of Aquaculture Centres in Asia-Pacific (NACA), Asian Development Bank, Earthquake and Tsunami Emergency Support Program, (ADB-ETESP), Banda Aceh, NAD, Indonesia	http://www.panglima.net/ conservation@gmai.com
K. Wikantika Director, Centre for Remote Sensing Chair, Indonesian Society for Remote Sensing (MAPIN)	Center for Remote Sensing, Institute of Technology Bandung (ITB), Indonesia	ketut@gd.itb.ac.id,
D. Mate Program Manager	Australia Indonesia Partnership for Reconstruction and Development (AIPRD), Local Governance and Infrastructure for Communities in Aceh (LOGICA) program	www.logica.or.id, office@logica.or.id
B. Coiron Project Engineer	Sogreah, Water Strategy 2007–2030 and Short-term Action Plan, Aceh and Nias Post Tsunami and Earthquake Reconstruction Program (ANTERP), Greater Banda Aceh—Housing and Infrastructure Reconstruction Program and Sector Strategies—Technical Assistance to BRR	bertrand.coiron@sogreah.fr
Richard Kidd Senior GIS Officer	Spatial Information and Mapping Centre (SIM-Centre), Badan Rehabilitasi dan Rekonstruksi (BRR) NAD-Nias, (Agency for Reconstruction and Rehabilitation of NAD and Nias)	sim.centre@brr.go.id

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Interim Report IR-09-011

GEO Information For Disaster Recovery - Case Study: The use of Orthophotos in Aceh, Indonesia

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18 September 2009

Abstract

This study, carried out between July-September 2008, looks specifically at the use of a high resolution aerial photograph (orthophoto) data set acquired in June 2005 over post tsunami Aceh, Indonesia. The study clearly demonstrates the benefit of the use of EO data for disaster recovery showing that the orthophoto data set, costing 1.4 million Euro, critically supported projects (primary users of the data set), worth over 16 times its actual cost (28 million Euro) and provided support to projects worth over 600 times its actual cost (880 million Euro).

The study concludes that a simple robust methodology to quantify the benefit of EO data in disaster recovery may be implemented by monitoring the total costs of projects that are critically supported by the EO data set. To implement that monitoring mechanism, a robust and straightforward method must be in place with the EO data distributor that records simple criteria for each of the data users and related projects.

The report provides a number of lessons that have been learnt from the spatial data initiatives between Official Development Agencies and the Government of Indonesia in response to the Tsunami. The report recommends that in order to ensure that the spatial data is used to its greatest benefit, prior to the initiation of any campaign, the donor funding the project must ensure that there is a defined and clearly proven, transparent, and accountable mechanism to ensure that the data is effectively delivered to the humanitarian aid community in a timely and efficient manner.

Acknowledgments

Our thanks go to M. Yakob Ishadamy and colleagues of the Spatial Information and Mapping Centre of the Badan Rehabilitasi dan Rekonstrucksi, Nanggroe Aceh Darussalam, Nias.

The authors would sincerely like to thank everyone who took time from their busy schedules working on their post tsunami reconstruction activities in Banda Aceh to participate in the interviews and those who provided further details.

We are also grateful that funding for this work was provided by the European Commission within the 6th framework via the (STREP) project "Global Earth Observation—Benefit Estimation: Now, Next and Emerging" (GEO-BENE; http://www.geo-bene.eu), Proposal No. 037063, Project Officer: Florence Béroud.

Executive Summary

The main aim of the study was to quantifiably assess the benefit of the use of a specific spatial data set in disaster recovery.

Within the Global Earth Observation System of Systems (GEOSS), the EU-funded project Geo-Bene (www.geo-bene.eu) is charged with estimating cost-benefits of Earth Observation (EO) data for nine societal benefit areas. One of these areas is titled *reducing loss of life and property from natural and human-induced disasters* Ref [1]. In an effort to better understand the benefits associated with using EO data in disaster regions, Aceh, Indonesia was selected as a case study within Geo-Bene.

The study, carried out between July-September 2008, looks specifically at the use of a high resolution aerial photograph (orthophoto) data set acquired in June 2005. The Norwegian Government funded (NORAD) orthophoto data set was completed in April 2006 and delivered to the Spatial Information and Mapping Centre (SIM-Centre) of the Indonesian Governments Rehabilitation and Reconstruction Agency (BRR) by the Indonesian National Coordinating Agency for Surveys and Mapping (Bakosurtanal) in August 2006.

In the following two years since delivery, the study shows that the data was delivered to 99 different projects in the rehabilitation and reconstruction community. The majority of the data set requests (primary users) came from the Government of Indonesia (37%), and Non Governmental Organisations (27%) with its use focusing largely on Urban or Rural Planning (48%) and Environmental Protection (16%). Approximately 90% of the primary users of the case study data found the case study data to be most important during the planning and operational phases of their projects.

This study clearly demonstrates the benefit of the use of EO data for disaster recovery showing that the orthophoto data set (costing 1.4 million Euro) critically supported projects (primary users of the data set), worth over 16 times its actual cost (28 million Euro) and provided support to projects worth over 600 times its actual cost (880 million Euro).

Aside from these primary users of the data set, over 635 secondary users of the data set (i.e. those requesting only derived products) were identified, including the use of the data set by over 400 professional and semi professional spatial data users during GIS training courses.

The main constraint of the case study data set was its delayed delivery by Bakosurtanal to the rehabilitation and reconstruction community in late 2006. At this time at least 44% of the reconstruction and rehabilitation of housing was completed, with reconstruction in other sectors being in an advanced state. This suggests that the data failed was not used in at least 44% of the main reconstruction sector. This sector, having an allocated budget of some 26% of the 5.8 billion dollar reconstruction budget[1], was the largest of the 13 reconstruction sectors, for which

[1] allocated by the end of 2006

the case study data was deemed ideally suited as a tool for coordination and planning.

The study concludes that a simple robust methodology to quantify the benefit of EO data in disaster recovery may be implemented by monitoring the total costs of projects that are critically supported by the EO data set. To implement that monitoring mechanism a robust and straightforward method must be in place with the EO data distributor that records simple criteria for each of the data users and related projects.

The report summarizes a number of lessons that have been learnt from the spatial data initiatives between Official Development Agencies (ODA's) and the Government of Indonesia (GoI) in response to the Tsunami in NAD. The report recommends that in order to ensure that the spatial data is used to its greatest benefit, prior to the initiation of any campaign, the donor funding the project must ensure that there is a defined and clearly proven, transparent, and accountable mechanism to ensure that the data is effectively delivered to the humanitarian aid community in a timely and efficient manner.

The report clearly demonstrates the benefit of the use of EO data for disaster recovery, and provides a simple and robust method by which its benefit can be quantified, verified and accounted to either donor or user communities.

Table of Contents

Acronyms and Abbreviations

ADB	Asian Development Bank
AIPRD	Australia Indonesia Partnership for Reconstruction and Development
ARRIS	Aceh Rehabilitation and Reconstruction Information System (JICA)
AT	Aerial Triangulation
AusAID	Australian Agency for International Development
BAKOSURTANAL	Badan Koordinasi Survei dan Pemetaan Nasional - (National Coordinating Agency for Surveys and Mapping)
BAPPEDA	Badan Perencanaan dan Pembangunan Daerah - (National Planning Agency)
BAPPENAS	Badan Perencanaan Pembangunan Nasional - (National Development Planning Agency)
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe -(Federal Institute for Geosciences and Natural Resources)
BPN	Badan Pertanahan Nasional - (National Land Administration)
BPS	Badan Pusat Statistik - (Statistics Indonesia)
BRR	Badan Rehabilitasi dan Rekonstruksi - (Agency for Rehabilitation and Reconstruction of NAD and NIAS)
CDA	Community Driven Adjudication
DAC5	Development Assistance Committee Coding Scheme 5
DCAS	Development Cooperation Analysis System (UNDP)
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
EO	Earth Observation
GEOSS	Global Earth Observation System of Systems
GIS	Geographic Information System
GTZ	Deutsche Geeselschaft fuer Technische Zusammenarbeit - (German International Development Agency)
IDR	Indonesian Rupiah
IFRC	International Federation of Red Cross and Red Crescent Societies
IFSAR	Interferometric Synthetic Aperture Radar
INS	Inertial Navigation System
IOM	International Organisation for Migration
IP	Internet Protocol
ISO	International Standards Organisation
JICA	Japan International Cooperation Agency
LAPAN	Lembaga Antarilesa dan Penerbangan Nasional - (National Aerospace and Aviation Association)
MDTF	Mutli Donor Trust Fund
MODIS	Moderate Resolution Imaging Spectroradiometer
NAD	Nanggroe Aceh Darussalam

NOAA	National Oceanographic and Atmospheric Administration
NORAD	Norwegian Agency for International Development
ODA	Official Development Assistance
OECD	Organisation for Economic Co-operation and Development
OGC	Open GIS Consortium
OWS	Open Web Source
PEMKO	Pemerintah Kota - City Government
PPC	Project Preparation Consultant (ADB)
PU	Departemen Pekerjaan Umum - (Department of Public Works)
PUSDATIN	PUSAT DATA & INFORMASI (BRR) - Office for Data and Information
RAND	Recovery Aceh Nias Database
RTRW	Rencana Tata Ruang Wilayah
SLGSR	Support for Local Governance for Sustainable Reconstruction (GTZ)
SPAN	Sensus Penduduk Aceh Nias - Census of Residents of Aceh and Nias
SPOT	Système Pour l'Observation de la Terre
SUMUT	Sumatera Utara
TEM	Transient Electromagnetic Surveys
TLM	Topographic Line Map
TRWMP	Tsunami Recovery Waste Management Programme (UNDP)
UNDP	United Nations Development Programme
UNIMS	United Nations Information Management Service
USAID-ESP	United States Agency for International Development - Environmental Services Program
USD	United States Dollars
USGS	United States Geological Service

Related Documents

1: IIASA Interim Report, IR-08-048, Banda Aceh - The Value of Earth Observation Data in Disaster Recovery and Reconstruction: A Case Study, 27 November 2008. On-line Report, http://www.iiasa.ac.at/Admin/PUB/Documents/IR-08-048.pdf (resource verified on 06/12/2008)

1 Introduction and Document Overview

1.1 Introduction

The main aim of the study was to quantifiably assess the benefit of the use of a specific spatial data set in disaster recovery.

Within the Global Earth Observation System of Systems (GEOSS), the EU-funded project Geo-Bene (www.geo-bene.eu) is charged with estimating cost-benefits of Earth Observation (EO) data for nine societal benefit areas. One of these areas is titled *reducing loss of life and property from natural and human-induced disasters* Ref [1]. In an effort to better understand the benefits associated with using EO data in disaster regions, Aceh, Indonesia was selected as a case study within Geo-Bene.

In this case study, the EO data set comprises high resolution orthorectified aerial photographs (orthophoto) acquired in June 2005 over the province of Nanggroe Aceh Darussalam (NAD), Indonesia, in the aftermath of the December 26^{th}, 2004 Tsunami (henceforth the Tsunami). The funding for the data set was granted by the Aid Development Arm of the Norwegian Government (NORAD) with the project being initiated, and managed, by the Indonesian National Coordinating Agency for Surveys and Mapping (Bakosurtanal).

The project to capture, create and deliver the orthophoto and spatial data was initiated in January 2005 and completed in August 2006. From August 2006 to July 2008 the whole, or parts, of the case study data set was distributed to 99 different primary data users and projects within the rehabilitation and reconstruction community in NAD. The study, reported in this document, to assess the benefit of the use of the case study data, was undertaken between July and September 2008.

The first step in quantifying the benefit of the use of the case study data was by means of a limited number of detailed interviews with technical managers responsible for the use of the case study data within their respective projects. The second step involved the creation and distribution of a detailed questionnaire to all primary data users to ascertain answers to the following questions:

- Who used the case study data
- How was the case study data used
- When was the case study data used
- What was the benefit of using the case study data
- What problems were associated with the case study data

The result of the study provides an applicable method for quantifying the benefit of the use of EO data in post disaster environments and provides development and donor agencies with an objective measure of the benefit in supporting spatial data capture campaigns in post disaster environments.

The study highlights some critical areas of concern in the implementation of similar data capture campaigns and provides a number of recommendations driven by observations from the management and delivery of the case study data.

1.2 Document Overview

An overview of the affect of the Tsunami within NAD is detailed in section 2. Following this, the requirements for the capture of new spatial data across NAD and the Nias Islands during the post disaster, emergency relief phase, are presented. Further details are also provided concerning the main responses and projects initiated by Official Development Agencies (ODA's) during 2005 to provide new, or enable access to, post disaster spatial data.

The project to acquire and deliver the orthorectified photography, forming the spatial data set of this study, is described in section 3. The description also includes an overview of the initial project objectives and deliverables, the actual project chronology, the methods by which access to the data set was enabled, and methods by which the data was distributed to the rehabilitation and reconstruction community.

In section 4, using information maintained by the data set distributors, a profile of the users of the case study data set and its' usage across the recovery community is presented. Some detailed examples on the use of the data set are presented in section 5.

The aims and rationale of the questionnaire concerning the actual usage of the case study data set are presented in section 6; the questionnaire itself is presented in 0. The results of the responses by agencies and projects technical managers to the questionnaire are summarised and presented in section 7.

A summary and discussion on the use, benefit and constraints of the case study data is presented in section 8. Conclusions on the benefit of the use of the case study data set are presented in section 9 along with recommendations how to implement a method to assess the benefit of the use of EO data in disaster recovery and recommendations to be followed by ODAs and donor agencies prior to funding or participating in spatial data campaigns.

2 Requirement for spatial data in post Tsunami rehabilitation and reconstruction in Nanggroe Aceh Darussalam

The earthquake and subsequent Tsunami devastated wide areas and hundreds of communities across Nanggroe Aceh Darussalam (NAD). In post Tsunami Nanggroe Aceh Darussalam the available topographic data (i.e. relief and the spatial location of man made and natural features) was approximately 30 years old and contained significant errors. Immediately after the Tsunami there was a large demand for up to date topographic and spatial data to support all of the rehabilitation and reconstruction activities. Some of the reconstruction activities that drove the requirement for updated spatial data are presented in section 2.1.The demand led to a number of initiatives between Official Development Agencies (ODA's) and the Government of Indonesia (GoI) specifically to collect spatial data in a number of ways. The main activities that were initiated in 2005 are presented in section 2.2. The NORAD funded orthophoto project was one of these initiatives.

The Tsunami devastated the coastal areas of the province of Nanggroe Aceh Darussalam (NAD) in Sumatra, Indonesia. It affected over 220km of coastline, damaging or destroying over 950 sq km of coastal area (640 sq km agricultural land, 150 sq km aquaculture), affecting some 300,000 parcels of land. Damage to property and infrastructure was also immense; over 600 villages, 12 % of the 4900 provincial villages, were affected; over 150,000 houses were damaged or destroyed; 8 hospitals and 114 health clinics were damaged or destroyed; approximately 50%, over 2100, of the provincial schools were damaged; 3000km of roads destroyed or made impassable; 120 arterial bridges destroyed and all major sea ports were destroyed or severely damaged. Over 140,000 people were killed and over 600,000 were displaced Ref [1], Ref [3].

2.1 The Demand for Updated Spatial Data

In the post Tsunami emergency relief phase during early 2005, the vast majority of the available topographical base maps for mapping purposes were obtained from the 1:50,000 national topographic map series from the National Coordinating Agency for Surveys and Mapping (Bakosurtanal). These maps were provided as hard copy products by Bakosurtanal.

These maps were derived from aerial photography flown in 1976 and were known to contain significant topographical errors. Considering that the Tsunami affected areas had also been ravaged by a civil war lasting over 30 years, the possibility to provide any update to this topographic data was also limited and no revisions were ever made to the original 1976 data. It is also obvious that during the intervening period there had been a significant changes in land use activities, especially so following the Tsunami. Also, as a result of the magnitude 9.1 Richter earthquake that triggered the Tsunami[2], there was a vast extent of differential rise and fall in ground levels, and,

[2] As reported by the United States Geological Service (USGS)

due to this, all existing topographical maps contained significant errors and were not suitable for engineering design work.

An assessment of priority mapping needs in NAD Ref [4] reported on the critical requirements for the update of topographic data. Spatial data and updated maps were essential for use in a wide range of planning and data collection purposes including the restoration of the ownership of more than 300,000 parcels of land which had been destroyed or for which evidence of ownership had been lost.

The report, Ref [4], notes that updated mapping was required to support a number of planning and reconstruction activities. Some of major activities are detailed in the following sections.

2.1.1 Master Plan Spatial Information Needs

The Master Plan for the Rehabilitation and reconstruction of the regions and communities of the Province of Nanggroe Aceh Darussalam and the Islands of Nias of North Sumatra, Ref [5], was published in April 2005. It identified several priority activities for which new mapping was required to progress the reconstruction program.

Chapter 5 of the Master Plan specifically relates to spatial mapping needs for the preparation of structure plans, mapping of land ownership boundaries, land consolidation, the green protection zone, mapping of pre- and post-disaster impacts and community based mapping of land occupied prior to the Tsunami. The need for new mapping was also closely related to other cross sector issues including land titling, compensation related to land matters, monitoring and evaluation of land use activities, sector policy development and disaster impact mitigation

2.1.2 Spatial Planning needs of local Government

Indonesian National Law 24/1992[3] requires that all government agencies prepare a range of spatial plans for development purposes, at specific scales as given in Government Regulation 10/2000 (see Table 1). Most of these plans are prepared by the National Development Planning Agency (Bappenas) and the National Planning Agency (Bappeda) at the provincial and district level, but also Public Works (PU), Provincial Environmental Agency (Bapedalda) and the National Statistics Agency (BPS) were also required to prepare a range of maps.

[3] The Spatial Planning Law 24/1992 stipulates the hierarchical spatial planning in Indonesia and consists of the national spatial plan (RTRW Nasional), the provincial spatial plans (RTRW Propinsi) and the district spatial plans (RTRW Kabupaten). All levels of the government are required to make spatial plans for directing the development in their respective regions. This law also differentiates spatial plans by the main function (i.e. environmental conservation - kawasan lindung) and the main activity of the area.

Type of Map	Scale
National	1:1000000
Provincial	1:250000
Special Area Provincial	1:100000 & 1:50000
City District (Kota, Kabupaten)	1:50000 contour + 50 m
City District (Kota, Kabupaten Special)	1:10000 + m
Village Sub-district (Desa, Kecamatan)	1:10000 + 12.5 and + 7.5 m

Table 1 Scale of Mapping Required by Government Agencies

2.1.3 Banda Aceh Action Plan

An action plan for Banda Aceh was required to identify areas needing priority actions, with a focus on reconstruction of housing and infrastructure services in devastated areas within the city. The action plan also identified a need for topographic digital and hardcopy base maps at scales between 1:10,000 and 1: 2,000 scale.

2.1.4 Village Development Mapping

More than 100 NGOs and community-based organizations were involved in a community based mapping program (CBM). An important step in the recovery process was the preparation of village or community development plans.

These plans, prepared at 1:5,000 to 1:10,000 scale, showed land use, infrastructure, drainage, emergency access routes and community facilities proposed to be developed for each village. The basis for preparing these plans were community-based maps which required that each parcel of land to be superimposed upon updated topographic base maps.

2.1.5 Fish Farm Maps

The Tsunami destroyed over 150 sq km of coastal fish farms (Tambak) and included a heavy loss of life amongst fishermen who owned or operated many of these farms. There was a need for a community based mapping approach to establish ownership of fish farms and reissues licences where these were held previously.

Pre- and post- Tsunami maps showing the location of boundaries and structures associated with fish farms were required to re-establish the aquaculture industry in the province.

2.1.6 Infrastructure Services

The damage to infrastructure (i.e. electricity, telecommunication, road networks, drainage systems and water supply services) caused by the earthquake and Tsunami was widespread across the province. The Ministry of Public Works (PU), responsible for the reconstruction of roads, drainage and other public utility services, required large-scale topographic and cadastral maps (1:1,000 to 1:5,000) to prepare detailed plans for the reconstruction and relocation of roads and other services.

2.1.7 Disaster Hazard and Risk Mapping

In order to prepare the province for other natural hazards and risks, selected areas of the province which are susceptible to tsunami, earthquake damage, landslide and subsidence, groundwater contamination and flooding and inundation needed to be mapped.

2.2 Activities in 2005 to Capture Spatial Data

During 2005 at the request of the Government of Indonesia (GoI) a number of Official Development Agencies (ODA's) provided support to address the need for the capture of spatial data and the provision of updated topographic data and products to the rehabilitation and reconstruction community.

A summary of the main activities initiated in 2005 to support the capture of spatial data are presented in the following sections[4].

2.2.1 Bakosurtanal

As primary custodians of national 1:50,000 to 1:250,000 topographic maps Bakosurtanal initiated a project to digitize this data and to make the data available to the rehabilitation reconstruction community. This data was available to National Governmental or UN agencies (only on request), in 2006.

2.2.2 LAPAN

One of the tasks of LAPAN (National Aerospace and Aviation Association) is for the reception of Landsat, MODIS and NOAA satellite imagery over Indonesia. LAPAN is also an authorised user of the International Space Disaster Charter and requested access to available satellite imagery acquired over NAD in early 2005.

A number of scenes from various satellites (SPOT, Landsat, Ikonos, ASTER) at various resolutions over various areas of interest were acquired via the Charter, ortho-corrected, and provided to Bappenas (National Development Planning Agency), however this was not made further available to the reconstruction community by Bappenas.

2.2.3 World Bank – RALAS

A US $28m program of assistance for a community-mapping program known as Reconstruction of Aceh Land Administration System (RALAS) was established by the World Bank via the Multi Donor Trust Fund (MDTF). Through Community Driven Adjudication (CDA) the program provided community based mapping to BPN (National Land Administration) to legally restore land titles and certification. A number of programmatic and legislative issues significantly delayed the progress of the project. The project is on-going at the time of this report.

[4] Note this ONLY reflects projects initiated in 2005 as an immediate response to the need for updated topographic and spatial data across the province of NAD and the Nias Islands

2.2.4 Asian Development Bank – ETESP

The on-going Earthquake and Tsunami Emergency Support Program (ETESP) of the Asian Development Bank provides rehabilitation and reconstruction support to mitigate the damages caused by the earthquake and Tsunami. The ETESP includes a strong mapping component providing strategic environmental assessment and monitoring of rural and urban communities to assess long-term impacts of the disaster. Specific spatial information requirements include land cover, land use and monitoring of the environmental impacts of reconstruction. A number of mapping activities including Sub-district Action Plans (spatial planning) and environmental impact and management plans were successfully completed and spatial data and maps made available to the rehabilitation and reconstruction community.

2.2.5 European Commission

The European Commission (EC) provided very high resolution pre and post Tsunami satellite imagery (Ikonos and Quickbird) and technical assistance to the National Land Administration (BPN) to perform ortho-rectification of imagery using precision Differential Global Positioning System (DGPS). Imagery was provided to BPN but access to the imagery, due to data licensing constraints, was withheld solely to BPN.

2.2.6 AusAID – IFSAR Mapping of Nias Island

The orthophoto project funded by NORAD (see section 2.2.10) was initiated prior to a second disaster occurring on the Islands of Nias. Nias, an island on the west coast of Sumatra, escaped the majority of damage of the 2004 Tsunami, but was greatly affected by a magnitude 8.7 Richter earthquake in March 2005. The urgent need to provide up to date topographic data was to be met by the capturing of airborne IFSAR (Interferometric Synthetic Aperture Radar) data and the production of high resolution digital elevation model (DEM) and at least 1:10,000 map products covering the whole island of Nias.

The AusAID funded IFSAR project was flown in June 2006 and also provided “gap-fill” map products in areas in coastal NAD not covered by the NORAD orthophoto project. The project included capturing new data over the city of Banda Aceh and its environs.

The project was completed in mid 2006. The IFSAR products and DEM’s were made available by Bakosurtanal to the reconstruction community in early 2007. This was possible only via the Spatial Information & Mapping Centre (SIM-Centre) of the Agency for Rehabilitation and Reconstruction of NAD and NIAS (BRR).

2.2.7 French Government Assisted Mapping

The French Government provided a grant to Bakosurtanal to tender a city mapping project. Based on the orthophoto imagery acquired under the NORAD funded project, (see section 2.2.10) and using detailed field surveys this project sought to create city map books at 1:10,000 scale of the five main Tsunami affected cities in NAD.

The project was completed in early 2007 and all products (40 1:10,000 maps sheets and associated spatial data) were provided to Bakosurtanal. The products were not provided to the rehabilitation and reconstruction community.

2.2.8 German Government – BGR

The German Bundesanstalt für Geowissenschaften und Rohstoffe, BGR, (Federal Institute for Geosciences and Natural Resources) undertook a detailed hydro-geological survey to assess groundwater resources within the river valley of Banda Aceh, and within water catchments around Calang, Meulaboh and Sigli.

After completion of an airborne geophysical survey (electromagnetic) and a hydro-geological reconnaissance survey maps were produced of the groundwater system to assess levels of saltwater contamination and potential yield. The data and all maps were made available to the rehabilitation and reconstruction community at the completion of the project in 2006.

2.2.9 Japanese International Cooperation Agency

The Japanese International Cooperation Agency (JICA) provided assistance to the BRR to prepare a draft spatial plan at 1:10,000 scale for Banda Aceh. Using post Tsunami high resolution satellite imagery from Ikonos and Quickbird new maps at 1:2000 scale were prepared for the most damaged sub districts of Banda Aceh. These maps included details of proposed new roads and land use activities. The data sets were integrated in a geographic information system (GIS) named Aceh Rehabilitation and reconstruction Information System (ARRIS) and, in 2005, was also provided to the United Nations Information Management (UNIMS) for dissemination to the wider reconstruction community.

2.2.10 Norwegian Government

The Norwegian Government, through it development agency Norad, funded Bakosurtanal to complete new imagery capture campaign and topographic mapping at 1:5,000 to 1:10,000 scale across 6500 sq km of NAD including the Tsunami affected area. After ortho-rectification of the 25cm resolution imagery, acquired in June 2005, topographic line maps (TLM) and digital elevation models (DEM) were derived.

The project was completed in April 2006 and the orthophotos and TLM data were provided, in August 2006, to the BRR for further distribution to the rehabilitation and reconstruction community via its SIM-Centre.

3 The NORAD funded Orthophoto project

The NORAD funded orthophoto project was initiated at the request of Indonesia's National Coordinating Agency for Survey and Mapping in January 2005. As detailed in section 3.1, the project to complete the capture of approximately 6500 sq km of digital imagery for the creation of 1:10,000 scale orthophotos was granted and funded by the Norwegian Government in March 2005. Although the onset of the project suffered from unforeseen delays, the project was completed in April 2006, and data was available to the rehabilitation and reconstruction community in August 2006. A fuller project chronology is presented in section 3.3. Upon delivery of the project deliverables to the BRR data access and dissemination was ensured to the rehabilitation and reconstruction community across NAD at no cost by the BRR's Spatial Information & Mapping Centre.

3.1 Project Overview

Following the International Aid conference in response to the Tsunami held in Jakarta, Indonesia, on the 4th and 5th January 2005, the National Coordinating Agency for Surveys and Mapping (Bakosurtanal) applied to the Norwegian Royal Ministry of Foreign Affairs (MFA) for a grant for a project to establish base maps and imagery required for the recovery of the devastated parts of Sumatra. The project was named "Creation of an emergency GIS for the Rehabilitation and Reconstruction of Nanggroe Aceh Darussalam (NAD) and Northern Sumatera (SUMUT)" Ref [6].

The project was funded in March 2005 by the Norwegian Agency for International Development (NORAD) with a grant of 13.700.000 NOK (1,729,798 Euro) being awarded to Bakosurtanal.

The project consisted of acquisition of aerial photography with a digital camera; survey of ground control points; production of digital terrain model (DTM); production of digital orthophotos and production of a digital base map in two different map scales. These deliverables are summarised in Table 2. The coverage of the project is shown in Figure 1. The project also saw for the delivery of a Geographic Information System (GIS) to handle the map data and imagery.

Description	**Coverage Area**
Aerial photography	6000 sq. km
DTM	6000 sq. km
50 cm. Orthophotos	5500 sq. km
25 cm. Orthophotos	500 sq. km
1:10,000 line mapping	3000 sq. km
1:5,000 line mapping	450 sq. km

Table 2: NORAD funded Orthophoto Project Deliverables

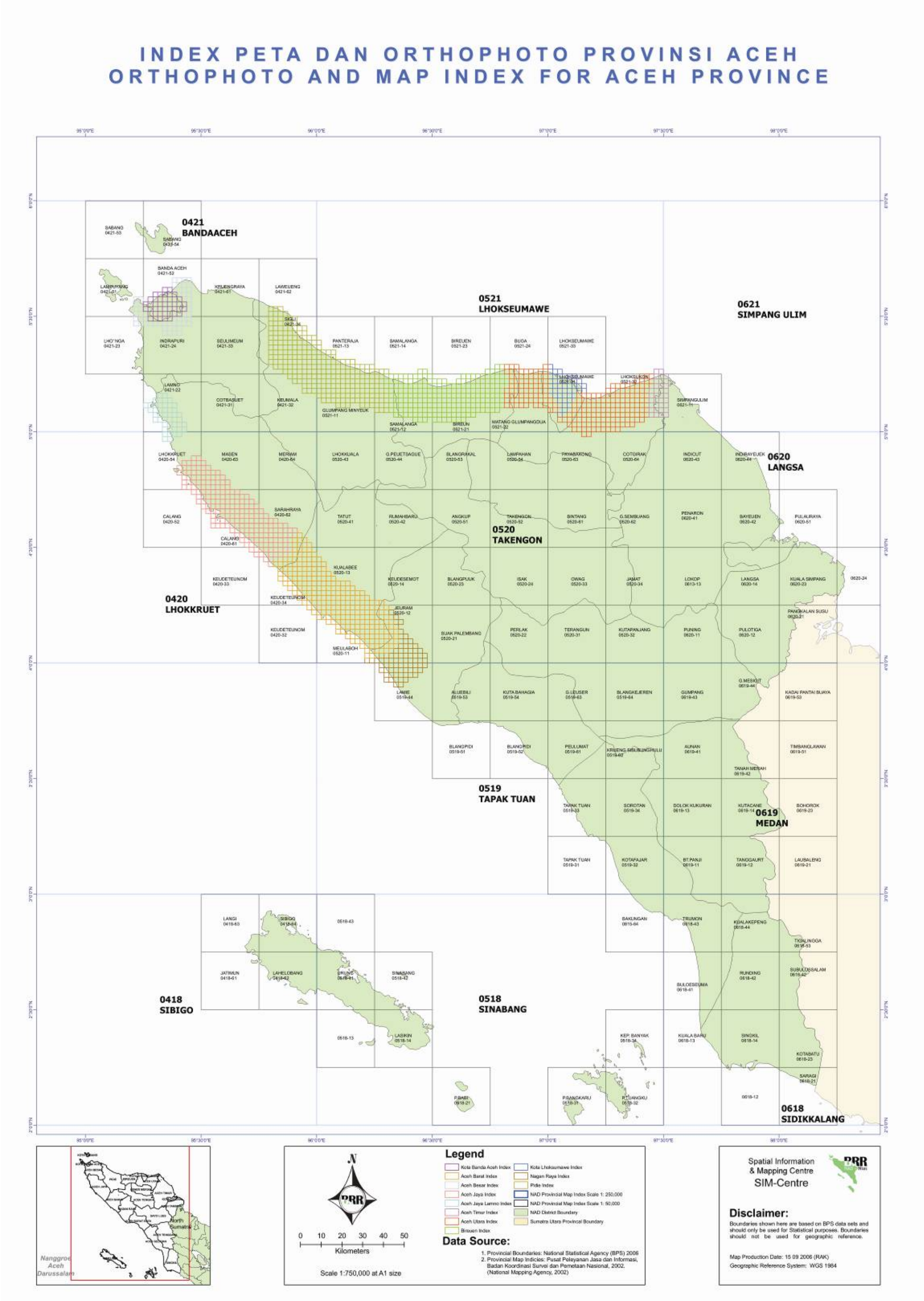

Figure 1 Location of NORAD orthophotos (case study data set) shown as small coloured boxes on coastal areas of Aceh Province (NAD)

3.2 Potential Data Users

The purpose of the project was to provide updated and reliable information on the actual status of the Tsunami affected and surrounding areas. The up to date spatial information provided by the project was seen to be crucial for the efficient use of the emergency aid funding, creating the base for the planning of the aid programmes as well as for monitoring and evaluating the programmes as they reconstruct and rehabilitate the province.

Aside from the general planning and coordination enabled by the use of spatial data a number of specific projects were identified as being key users of the data:

- Town planning;
- Land titling;
- Infrastructural Reconstruction (harbours, dams, roads etc., including cut-and-fill calculations).

Noting that all detailed engineering design (DED) for infrastructural projects (i.e. at scales better than 1:5,000) would have to be followed up by dedicated field surveys prior to implementation of final rehabilitation and reconstruction projects

3.3 Project Chronology

The project was initiated at the request of Bakosurtanal in January 2005, a grant was made available in early March 2005 by the Norwegian Agency for International Development (NORAD), and the project contractor (BLOM Info) was hired in mid March 2005.

After a number of delays (due to issues obtaining correct military security clearance for permission to fly) the flight campaign was started in late May 2005. Image acquisition was completed in July 2005, and imagery delivered to Bakosurtanal in September 2005. The first orthophoto mosaic (Banda Aceh) was delivered in mid November 2005, the orthophoto mosaic for West Coast in January 2006, and finally the East Coast in April 2006. A small number of areas were deemed to be of a nationally sensitive nature and were not given military approval for release. These areas were not included in the delivered orthophoto mosaics. Final deliverables were completed to Bakosurtanal in April 2006. The total invoiced cost of the project was just over 1.43 Million Euro

Project deliverables consisting of orthophoto mosaic and line mapping were provided to the BRR (Spatial Information & Mapping Centre, SIM-Centre) by Bakosurtanal for distribution to the aid and recovery community in Aceh in mid August 2006. Digital Elevation Models (DEM or DTM) were not provided for distribution by Bakosurtanal. A more detailed project chronology is provided in Table 3.

Date	Event
04/01/2005	International Aid Conference in Response to 26/12/04 Tsunami, Jakarta
12/01/2005	Bakosurtanal application to Royal Norwegian Ministry of Foreign Affairs (MFA) for project "Creation of an emergency GIS for the rehabilitation and reconstruction of Nanggroe Aceh Darussalam (NAD) and Northern Sumatra (SUMUT)"
04/03/2005	Letter of exchange established between Royal Norwegian Embassy (Jakarta) and a grant of 13.700.000 NOK (1,729,798 Euro) awarded to Bakosurtanal. Funding provided through Norwegian Agency for International Development (NORAD)
16/03/2005	Bakosurtanal and Blom ASA sign contract to initiate project
05/2005	Initial grant payment (75%) by MFA to Bakosurtanal
27/05/2005	Start of Aerial Photo acquisition campaign
12/07/2005	All raw data from completed aerial photo flight was handed over to Bakosurtanal
21/09/2005	Delivery of all imagery including Global Positioning System (GPS), Inertial Navigation System (INS) data after Aerial Triangulation (AT)
10/2005	Final grant payment (25%) by MFA to Bakosurtanal
16/11/2005	Delivery of Orthophotos and Digital Terrain Model (DTM) and 25 cm orthophotos for 537 sq. km (Banda Aceh and Lamno)
30/01/2006	Delivery of Orthophotos and Digital Terrain Model (DTM) and 25 cm orthophotos for 2285 sq. km (West Coast)
22/03/2006	Line mapping 1:5.000 for 537 sq. km (Banda Aceh, Lamno)
19/04/2006	Delivery of Orthophotos and Digital Terrain Model (DTM) and 25 cm orthophotos for 3427 sq. km (East Coast)
25/04/2006	Delivery of line mapping 1:10.000 for 3015 sq. km (West Coast and East Coast)
17/05/2006	Approval of Emergency GIS hardware and software installed at Bakosurtanal
14/08/2006	Delivery of all orthophotos and line mapping data by Bakosurtanal to BRR, Banda Aceh (Spatial Information & Mapping Centre)

Table 3 Chronology of Events and Deliverables for NORAD funded Orthoimagery for NAD

3.4 Data Distribution to the Rehabilitation and Reconstruction Community

In mid August 2006 the Spatial Information & Mapping Centre (SIM-Centre) of the BRR were tasked by Bakosurtanal to be the point of distribution for the orthophoto mosaic and line mapping data to all agencies within the rehabilitation and reconstruction community in NAD.

The data set is regarded as a national data set and as such comes under strict Military and National Security control. Due to this sensitive nature of the data, stringent procedures comprising user registration, verification of requirement for data, and data user agreement, were established at the SIM-Centre to ensure that rigorous tracking of primary data users was maintained.

At the end of 2006 the GIS software that was also delivered to Bakosurtanal was customised and installed at the SIM-Centre, BRR. The software, a web based solution (WebGIS), was based on Open Geospatial Consortium (OGC) compliant Open Web Source (OWS) architectures and enabled clients simple and direct access to the orthophoto mosaic, without the need for costly or technically demanding software installations.

Limitations in bandwidth, and connectivity issues, across Banda Aceh and NAD initially restricted this application to an intranet application accessible only within the BRR, but the improvements in IT infrastructure across NAD in 2007 and 2008 saw the application move to a more accessible and stable platform within the Governor of Aceh's office (http://www.webgis.nad.go.id/).

In this manner the SIM-Centre ensured that the rehabilitation and reconstruction community had access to data in three manners:

- Data could be provided in digital format ready to be integrated into clients in-house GIS solutions (primary data user)
- The data could be provided as customised hardcopy (printed) or softcopy (digital) made to order bespoke maps (secondary data user), or
- Data could be accessed digitally and queried on-line (secondary data user).

The provision of the case study data, or creation of maps from the case study data, and the on-line access to the case study data was provided, by the SIM-Centre, at no cost to the rehabilitation and reconstruction community.

Bakosurtanal also maintained its own methods to distribute the data to the rehabilitation and reconstruction community in NAD.

4 Overview of Data Users and Data Usage

As noted in section 3.4 the data set was either distributed directly as an electronic data set to users, was provided as a customised product or access was enabled for users electronically via intra, or internet applications. Users who were given digital (soft) copies of the data set are termed primary data users, whilst users obtaining the data in another manner are termed secondary data users.

During the period August 2006 to July 2008 there was a total of 99 recorded primary data users and over 635 secondary data users. It is also noted that the data set was used as a core data set in GIS training provided to local government officials, and as such a wide range of professional and semi professional spatial data users were also exposed to the data set.

4.1 Primary Data Users

During the period August 2006 to July 2008 the SIM-Centre provided the orthophotos and associated data (line maps) to 79 users. The usage category and organisation type are summarised in Table 4 and Table 5. It is also known that Bakosurtanal provided orthophoto data sets to 20 further projects but due to insufficient information concerning project type or data usage from 18 of these projects they are not included in Table 4 and Table 5, and are not included further in this study

The total number of primary data users (projects) included within this survey is therefore 81. This comprises 79 primary users with the data set provided by SIM-Centre, and 2 primary users with the data set provided by Bakosurtanal.

Primary data users were obliged to provide project details, which were confirmed with independent project registration maintained within the Recovery Aceh Nias Database (RAND) of the BRR. For this study the description of the project type (usage category) has, where possible, been categorised using the DAC5 coding (Development Assistance Committee Coding Scheme 5) maintained by the Organisation for Economic Co-operation and Development (OECD). This categorisation is an integral part of the OECD's credit reporting system (CRS) and the DAC5 project type coding for humanitarian aid projects is the current standard between Official Development Assistance (ODA) agencies and the United Nations (UN)[5]

The four largest usage categories, as shown in Table 4, are for Urban or Rural Planning (other multisector), Environmental Protection, Project Planning and Transportation and Storage projects.

[5] For more information please refer to the United Nations Development Programme (UNDP) Development Cooperation Analysis System (DCAS)

Usage Category	Notes	DAC5 Code	Percentage of total
Agriculture		311	1.23
Basic Health	Malaria Monitoring	122	1.23
Data Provider		-	1.23
Forestry	Reforestation	312	1.23
Environmental Protection		410	16.05
Other Multisector	Urban and Rural Planning	430	48.15
Project Planning		-	7.41
Reporting		-	3.70
Research		-	4.94
Transport and Storage	Road Construction	210	6.17
Unallocated/Unspecified		998	4.94
Water Supply and Sanitation	Water Supply Systems, Basic Water Supply	140	3.70

Table 4 Orthophotos Users by Project Category

Similarly a categorisation of the primary data users by organisation type is presented in Table 5. In this study organisations have been categorised in the following manner:

- **GOI:** Government of Indonesia, including the BRR and any Indonesian Government agency
- **Donor:** A funding agency not directly responsible for the physical implementation of projects e.g. United States Agency for International Development (USAID)
- **IO:** International Organisation, or Intergovernmental Agency e.g. Asian Development Bank (ADB), International Organisation for Migration (IOM), or International Federation of Red Cross and Red Crescent Societies (IRFC)
- **NGO:** Non Governmental Organisation[6], includes International Non Governmental Organisation, and implementing arms of government e.g. German International Development Agency (GTZ)
- **UN:** United Nations Agency i.e. United Nations Development Programme (UNDP)
- **Others:** Including Universities or private contract Companies not working for any of the organisations mentioned in the other categories.

[6] also known as “not for profit organisations”

Organisation	Percentage
Government of Indonesia (GOI)	37.04
Donor	7.41
International Organisation (IO)	6.17
Non Governmental Organisation (NGO)	27.16
United Nations (UN)	13.58
Others	8.64

Table 5 Orthophotos Users by Organisation

As shown in Table 5 the three main organisation types that requested use of the case study data set are Government of Indonesia, Non Governmental Organisations and the United Nations.

4.2 Secondary Data Users

Although not all agencies within the rehabilitation and reconstruction community had in-house expertise (specifically GIS expertise, or software) to manage the case study data set, there was still a requirement for access to products derived from the case study data set. In general, these products were created upon request and delivered to the requesting agency by the SIM-Centre.

Once the case study data set had been transformed into a spatial data product i.e. a map or incorporated into a GIS data set, other than the electronic data sets (deliverables) mentioned in Table 2, it is termed here as secondary data. Although there was no requirement by Bakosurtanal to maintain a rigorous track of these secondary data users they are included in the following brief sections in this report.

4.2.1 Creation of Maps

A total of 113 maps were created and delivered to agencies within the rehabilitation and reconstruction community (SIM-Centre 93%, Bakosurtanal 7%). As shown in Table 6 large format maps were the most frequently requested, with the largest demand coming from NGO's Table 7.

This summary only includes maps that were created solely from the case study data set i.e. the orthophotos, and does not include maps that used GIS data or topography created or derived from TLM and DEM deliverables mentioned in Table 2. The summary also does not include maps that used the orthophotos purely as a means of visualisation of local topography e.g. simple visit and route maps.

Map Size[7]	Percentage
A4	10
A3	17
A2	8
A1	64

Table 6 Secondary Data Users: Orthophoto Maps Created[8]

Organisation	Percentage
Government of Indonesia (GOI)	43.5
Donor	
International Organisation (IO)	
Non Governmental Organisation (NGO)	50.5
United Nations (UN)	3
Others	3

Table 7 Secondary Data Users: Orthophoto Maps Requested

4.2.2 Access to on-line web mapping application

An on-line web mapping application, enabling access to the case study data set was initially hosted as an intranet application by the SIM-Centre at BRR. Due to numerous problems with local power outages and instability of local intranet within BRR no records were maintained concerning the number of users accessing the BRR intranet application.

In 2008 as the IT infrastructure across the province of NAD became more stable (as noted in section 3.4), the on-line intranet application originally hosted by the SIM-Centre was moved to an internet application hosted from the office of the governor of Aceh. During the first two months of its operation from July to August 2008 the web application hosted at http://webgis.nad.go.id/ saw approximately 100[9] instances of use.

4.2.3 Training Data

The case data set was also used, in part, as a training data set during 19 of the GIS training courses provide by the SIM-Centre of the BRR to a total of 422 local government staff. As such, the professional and semi-professional spatial data users participating in the training courses can be considered to be secondary users of the case study data set.

[7] Based on standard "A format" ISO 216 paper size

[8] not including Bakosurtanal clients, for which no information was available

[9] Noted from the host server access logs as unique IP addresses actively accessing the application website

5 Example uses of the case study data

A sample of the primary data users were informally interviewed to obtain a broader picture of how the case study data had been used within their projects. The sample of primary data users that were selected for interview was selected from the members of the GIS User Group forum. The GIS User Group forum was an open group representing the interests of all professional GIS and spatial data users across the rehabilitation and reconstruction community. The sample of primary data users are representative of the professional GIS and spatial data users within the rehabilitation and reconstruction community within NAD.

The interviews were conducted in person by the author with the technical manager of each project, and the results of the interviews are presented in the following sections. Comments raised and points discussed in the interviews were used to aid in the design of the questionnaire (see section 6), which was later distributed to all primary data users.

5.1 Asian Development Bank – Earthquake and Tsunami Emergency Support Program (ETESP)

The Earthquake and Tsunami Emergency Support Project (ETESP) of the ADB used the case study data in four of their projects. The data was used to support their Spatial Planning and Environmental Management project, Agriculture Sector, Fisheries Sector and Road and Bridges project. Specifically the projects looked to the preparation of Kecamatan Action Plans (sub-district level), for 19 Sub-districts; the rehabilitation and reconstruction of livelihoods assets post Tsunami in both agriculture and fisheries sectors; support to fisheries rehabilitation across 11 district and towns in Aceh and Nias and the creation of the design and project preparation documents for 22 km of road segments on the East Coast Road of NAD and the within the city of Banda Aceh.

The four projects had over 125,000 direct beneficiaries and cost a total of over 79 Million Euro. The case study data was used, to some extent, in all five phase of the project lifecycle (i.e. project initiation, planning, operation, monitoring and evaluation and project closure) across each of the projects, but was most significantly used in the operational phase of the projects. Over 85 maps were created within the projects from the case study data set and GIS data sets were also derived.

The case study data set was deemed to be a critical factor in the successful completion of one of the projects, whilst the case study data set supported the completion of the other three projects. In the case where the data was considered to be critical to the successful completion of one of the projects, it was estimated that it would have cost 12,000 Euro to obtain the same information from a different data source.

The main issues that were raised about the use of the case study data set concerned;

- Long delivery time for the orthophoto product, meaning that the data set could not be used in project initiation phases,

- Given the quick developments of reconstruction and redevelopment in the Tsunami affected areas data was out-of-date, and
- Incomplete coverage by the case study data set of coastal areas that were also affected by the Tsunami

5.2 German International Development Agency (GTZ)

The German International Development Agency (GTZ) used the case study data in three of their projects. The case study data was used in their Support for the Local Governance for Sustainable Reconstruction (SLGSR) program for spatial planning activities. The three projects looked at sub district planning, integrated spatial planning for regional development planning and a development planning forum. The projects supported over 100,000 beneficiaries and cost over 400,000 Euro to implement. The case study data was used all of the five project phases, with the data being of most use in the planning and operation phases of the projects.

The main priority activities that the case study data were directly used for included: creation of village maps for collection of input from local community and stake holders, Atlas development, site survey for current land use, development and creation of land use map, creation of maps for public consultation and bottom up planning, identification and delineation of sub-district boundaries, and as input for sub-district spatial planning

The case study data was seen to be critical in the development planning forum whilst it supported the completion of the other projects. Within the development planning forum it was used to create an atlas to showing proposed planning by local communities and it was estimated that it would have cost some 16,000 Euro to obtain the same information from a different data source.

5.3 Management of GeoHazards in Nanggroe Aceh Darussalam (ManGEONAD)

The ManGeoNAD project is part of the German Indonesian technical cooperation between the Indonesian National Geological Agency, the Department for Mining and Energy for NAD (Distamben) and the German Federal Institute for Geosciences and Natural Resources (BGR). The project focuses on the collection and preparation of geological base data for the reconstruction process, provision of technical information and expert knowledge for spatial planning institutions, institutional strengthening, and has a comprehensive focus on the awareness raising of the population about natural hazards and geo-risks across NAD.

The case study data set was widely used in the project, largely in the planning and operational phases, and was considered to be critical to the successful completion of the 4 Million Euro project.

The data was used in the production of (potential) risk maps, to assist site selection to identify areas for excavation of raw construction materials, to assist for site selection for fresh water well drilling for various NGO’s, for site selection for location for seismic measurements, for site selection for transient electromagnetic surveys (TEM), as training data in GIS training courses, as visualisation data in maps and as sample and verification data to support remotely sensed data sets. The case study data set was incorporated in a GIS and it is estimated that maps created were used in excess of 150 times throughout the project.

To obtain the same information for other sources is estimated to cost in excess of 60,000 Euro. In general there were no issues with the use of the data, but it was noted that spatial accuracy of the data in some cases was not sufficient, and that data attributes, specifically in the TLM data sets was not complete.

5.4 United Nations Development Programme UNDP - Tsunami Recovery Waste Management Programme

The United Nations Development Programme (UNDP) through its Tsunami Recovery Waste Management Programme (TRWMP) began the program for the Agriculture land clearances in January 2006. The program cost over 1.5 Million Euros and support 2600 families as direct beneficiaries.

At the time of this report there remains an estimated 26,000 ha (260 sq km) of agricultural land which cannot be cultivated due to heavy deposits of sand, silt and debris blanketing the land, and blocking the irrigation channels and drains. In places the deposits can be up to 50cm thick and heavy equipment is required to assist the farmers to clear the land and restart agriculture. The TRWMP has used numerous spatial data sets, including the case study data set, to locate areas in greatest need of land clearance, and to work with farmers and community leaders to demark field boundaries, canals and drains.

The case study data is also used as a primary mapping tool to determine areas and potential volumes of waste that must be moved and to prepare clearance plans. This information is critical for preparation of heavy equipment contracts required for land clearance. The case study data is critically used primarily for project planning, operation, and monitoring and evaluation and is estimated that it would cost approximately 200,000 Euro to obtain the same information from different sources. There were some minor issues with the case study data being affected by cloud cover.

6 Design and Delivery of Questionnaire

The questionnaire 0 was designed to retrieve information from the case study data users to determine answers to the following study questions:

Study Qu. 1. Which category of organisation were the main users of the case study data?

Study Qu. 2. What type of project required the case study data and how was it used within projects?

Study Qu. 3. At which phase of the project life cycle was the use of the case study data most significant?

Study Qu. 4. What was the benefit of using the case study data?

Study Qu. 5. What were the problems with the case study data set?

The following section outlines the design of the questionnaire, the aims of the questions within the questionnaire and details how, and to whom, the questionnaire was delivered.

6.1 Design of the Questionnaire

The questionnaire design was intentionally simple to encourage a high completion and return rate. The respondents were encouraged to respond by providing clear examples of responses to the majority of questions and where possible a number of predetermined responses to questions were included. In questions with multiple responses a clear ranking of the responses was required and explained. The questionnaire was tested and modified before being finalised, translated into Bahasa, Indonesian and distributed.

The design of the questionnaire showing the logical flow of responses is presented in Figure 2, with the English version of the questionnaire being presented in 0 Only four of the eleven questions were expected to be completed by all primary data users, as noted by the shaded boxes in Figure 2.

One of the following four outcomes were expected from each questionnaire distributed to the primary case study data users:

Outcome 1: No response

Outcome 2: Case study data set was acquired by user but not used in project

Outcome 3: Case study data set was acquired and used by user but its use was not critical to the successful completion or operation of the project

Outcome 4: Case study data set was acquired and used by user and its use was critical to the successful completion or operation of the project

From outcome 2 the respondent would only complete five questions: 1, 2, 3, 10 and 11. From outcome 3 the respondent would complete nine questions: 1,2,3,4,5,6,7,9,11, and from outcome 4 the respondent would complete ten questions: 1,2,3,4,5,6,7,8,9,11.

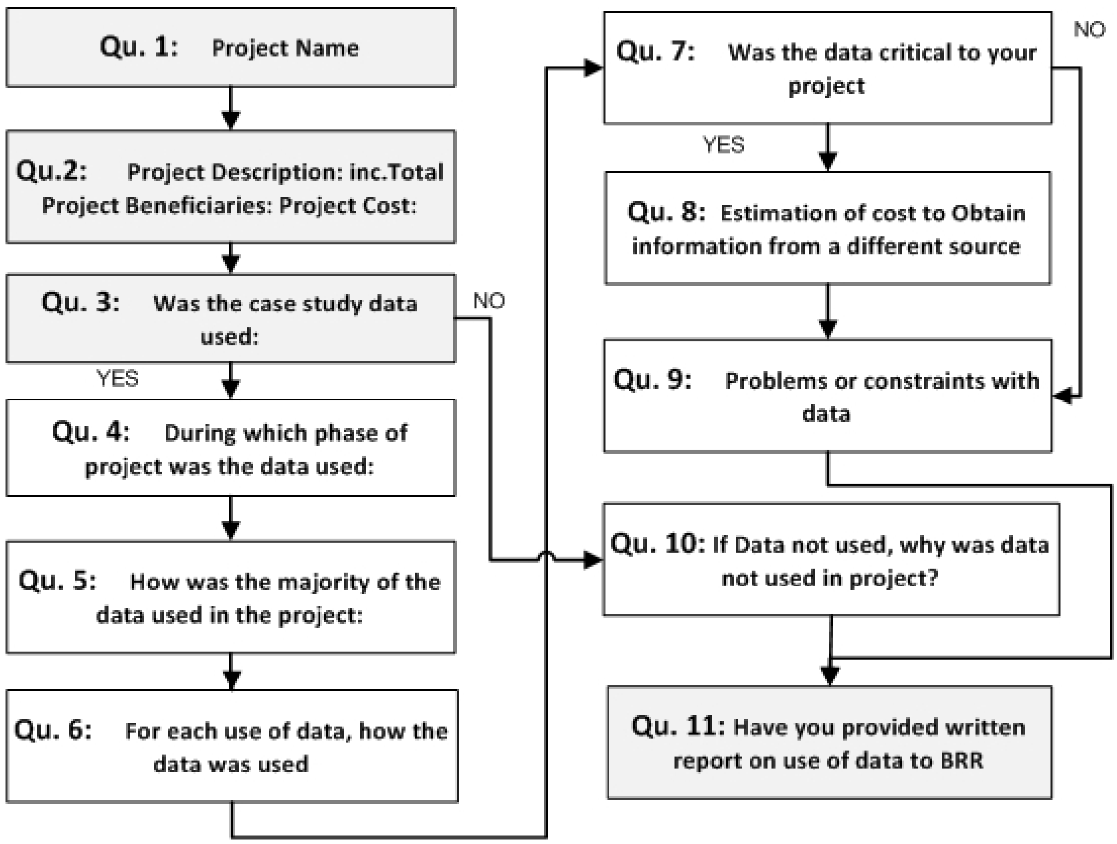

Figure 2 Questionnaire Design, showing logical flow of responses

6.2 Question Objectives

With the exception of self explanatory questions this brief section provides an overview of the objectives of the questions contained in the questionnaire 0:

Question 2: Aimed at retrieving a short narrative about the project, its' aims and objectives, and specifically requested details on the total number of project beneficiaries, the area (sq km) covered by the project, the project duration (months), and the total project costs (expressed either financially or in terms of months of effort allocated to the project).

Question 3: Determines if the case study data was actually used within the project.

Question 4: Aimed at retrieving information during which of the standard five phases of the project lifecycle (i.e. project initiation, planning, operation, monitoring and evaluation and project closure) was the data used. If the data was used in more than one phase, then a ranking of importance of use (most important 1, least important 5) was requested.

Question 5: Determined if the majority of the case study data was used either as map products or was integrated in a GIS, and requested the frequency of the use of these products.

Question 6: Aimed at retrieving a more detailed narrative on the actual use of the case study data in the project, with a ranking on the importance of the use of the data, as in question 4, being requested.

Question 7: Determined if the case study data was critical to the operation of the project, or just used as a supporting ancillary data set. The use of the case study data set was deemed to be critical if without the case study data set the project would not run, or the project would not be effective.

Question 8: Where the case study data set was critical to the project, this question aimed at retrieving a narrative on how the information acquired from the case study data set would have been obtained if the case study data set was not available. The respondent was also required to provide an estimate (either financial, or in months of effort) of the cost of obtaining the information from the alternative source they described.

Question 9: Aimed at collecting feedback concerning any problems or constraints with the case study data set.

Question 10: If the case study data set was not used in the project, this question aimed at retrieving the reason why the case study data was not used. For ease of completion five predetermined reasons were provided.

Question 11: The final question was included to prompt all registered case study data users that they were required (by the data user agreement signed upon receipt of the case study data), to provide feedback on the use of the case study data to the BRR.

6.3 Delivery of the Questionnaire

In assessing the benefit of the use of the case study data set, only primary users were contacted as these projects were likely to have made fuller use of the case study data rather than the secondary users. The questionnaire and covering letter, providing an overview of the aims of the questionnaire, were delivered by e-mail to the registered user[10] of the case study data set. Considering the broad spectrum of both national and international agencies recorded as primary data users both covering letter and questionnaire were provided in both Bahasa Indonesia and English.

The questionnaire was created as an MS office word document with dedicated free text fields for responses, and respondents were required to return the completed questionnaire as an MS office word document. All respondents were also required to provide complete contact details to ensure follow up was possible if required.

From the initial 81 case study set primary users, as noted in 4.1, only 48 of the primary users (as recorded in their data user agreement) had valid, functioning e-mail addresses. Of the remaining primary users 23 had bad or invalid e-mail addressed which could not be traced[11] and 10 did not have, or had not provided, e-mail addresses. The questionnaire was delivered to 48 primary users, the respondents being allowed two weeks deadline to respond. Two weeks after the submission deadline a reminder for responses was provided to all who had not responded.

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[10] As recorded in the data user agreement between the user and the SIM-Centre

[11] With a large number of consultants working on short duration of contracts within both national and international agencies there was a high turnover of staff in the rehabilitation and reconstruction community, leading to a large number of work related e-mail addresses having a limited duration validity.

7 Summary of Results from the Questionnaires on the use of Orthophotos in Rehabilitation and reconstruction

The following section presents the analysis of the results of the questionnaires that were delivered to primary users of the case study data set.

After looking at the response to the questionnaire, answers to the study questions presented in section 6 are delivered.

7.1 Response to Questionnaire

After follow up with the 48 primary users to whom the questionnaire was successfully delivered, 23 completed questionnaires were received giving a response rate of 48%. All of the respondents stated that their project had used the case study data set to support their project activities in some manner.

A breakdown of the responses received by organisation and project type are presented in Table 8 and Table 9.

Organisation	**Percentage Requested data**	**Percentage Questioned**	**Percentage Response**
GOI	37.0 %	35.4 %	26.0 %
DONOR	7.4 %	6.3 %	8.7 %
IO	6.2 %	4.2 %	17.4 %
NGO	27.2 %	31.3 %	34.8 %
UN	13.6 %	16.7 %	8.7 %
Others	8.6 %	6.3 %	4.3 %
Total Number	**81**	**48**	**23**

Table 8 Responses received by organisation type

Although the largest percentage of the questionnaires were sent out to Government of Indonesia Agencies, the largest percentage of the questionnaires that were completed and returned came from International Organisations and NGO's. The UN Agencies also showed a relatively low return of completed questionnaires.

DAC5 Usage (Code)	Note	Percentage Requested data	Percentage Questioned	Percentage Response
Agriculture (311)		1.23	2.1	4
Basic Health (122)	Malaria Monitoring	1.23	2.1	-
Data Provider		1.23	-	-
Forestry (312)	Reforestation	1.23	2.1	-
General Environmental Protection (410)		16.05	20.8	22
Other Multisector (430)	Urban and Rural Planning	48.15	47.9	52
Project Planning		7.41	6.3	4
Reporting		3.70	4.2	-
Research		4.94	4.2	4
Transport and Storage (210)	Road Construction	6.17	8.3	13
Unallocated/Unspecified		4.94	-	-
Water Supply and Sanitation (140)	Water Supply Systems	3.70	2.1	-
	Total	**100%**	**100%**	**100%**

Table 9 Responses received by project categorisation

The percentage of questionnaires sent to various project types and the percentage of questionnaires received from project types are very similar. The notable exceptions being that no responses were received from projects focusing on basic health, forestry and water supply and sanitation.

7.2 Data Users

Study Question 1: Which category of organisation were the main users of the case study data?

As shown in Table 8 the largest percentage of requests for the case study data came from the Government of Indonesia Agencies, but the results from the questionnaire can only confirm that the GoI were a main user group of the data and that NGO's were the largest user of the case study data set.

7.3 Data Usage

Study Question 2: What type of project required the case study data and how was it used within projects?

The percentage break down of the types of projects that requested and used the data, as shown in Table 9, are very similar. The case study data has been mainly used for Urban and Rural planning purposes, and general environmental protection projects, but the range of projects supported vary from Agriculture, Research, and Transport projects.

The type of activities that were undertaken with the case study data were wide and varied, as demonstrated by the examples presented in section 5. The questionnaire requested a detailed description of the type of activity that was undertaken with the case study data set. The frequency of the use of a number of keywords in the description of the activities were used to analyse the responses, these are shown in Table 10. Only the six most frequent keywords are shown.

Keyword	Occurrence[12]	Percentage
Maps	10	22
Survey	7	16
Identification	6	13
Planning	4	9
Report	4	9
Site Selection	3	7

Table 10 Types of activities undertaken with the case study data set

It is clear that the case study data was used largely for mapping, surveying or identification of features relevant to the projects. From specific responses to question 5 of the survey 95% of the respondents claimed to use the case study data to produce maps, with over 300 uses of the maps, and a further 65% claimed to integrate the case study data within a GIS.

7.4 Timeliness of Data Usage

Study Question 3: At which phase of the project life cycle was the use of the case study data most significant?

The case study data was used across the entire five standard project phases i.e. project initiation, planning, operation, monitoring and evaluation and project closure. The percentage usage of the case study data in the project phases and the relative importance of the use of the case study data (1 important, 5 not important) is presented in Table 11.

	Project Phase				
	Initiation	**Planning**	**Operation**	**Monitoring and Evaluation**	**Closure**
Percent Usage	74	92	87	70	78
Average	3.1	1.6	1.3	2.5	3.1

Table 11 Use of case study data in project phases and relative importance (1 important, 5 not important) of usage of case study data in each phase

[12] Although only 23 questionnaires were completed, each respondent detailed a number of activities. A total of 45 activities were explicitly mentioned.

It is clear that almost all the projects used the case study data in the planning and operational phases of the project, and that the operational and planning phases were where the case study data was of most importance to the projects.

7.5 Benefit of Data Usage

Study Question 4: What was the benefit of using the case study data?

Two methods were used to quantify the benefit of the use of the case study data set. The first method, described in section 7.5.1, uses an attribute from the project to assess the overall benefit of the project and then determines if the use of the case study data was critical to the successful completion of the project.

The second method, described in section 7.5.3, looks at what information was derived from the use of the case study data set and determines the real cost to acquiring that information from another source. This was only calculated where the use of the case study data set was deemed to be critical to the successful completion or operation of the project.

7.5.1 Determination of benefit of the use of the case study data set based on project attribute

The second question of the questionnaire was designed to enable the respondents to provide a number of easily calculated figures, or project attributes, which could be either used directly, or indirectly, to quantify the benefit of the use of the case study data. Respondents were asked to provide the following attributes;

- information on the number of direct project beneficiaries (i.e. number of families, or number of persons, that would receive a direct improvement in their current situation as a result of the completion of the project)
- information on the physical extent and coverage of the project area
- information on the total cost of the project
- information on the duration of the project

Not all respondents provided complete information for the requested attributes. The percentages of responses are shown in Table 12.

Attribute	Percentage Response
Beneficiaries	39
Coverage	74
Duration (months)	91
Cost	87

Table 12 Percentage of respondents providing project attributes

Upon reviewing the responses it was found that the most incomplete and unreliable attribute to determine benefit was that for the number of direct project beneficiaries. As can be seen from Table 12 only 39% of respondents provided this attribute, and in some cases the responses were overly optimistic; some even claiming that their project directly benefited all the 4,031,589[13] residents in the province of NAD, or all of the estimated 203,998 people who were directly affected by the Tsunami.

It was also found that responses for the attribute of coverage of the project was also unreliable, again, with some responses claiming that their projects had a direct impact on the complete 61,061 sq km of the province, whilst others presented more realistic and verified values.

The attribute for duration of project was the most comprehensibly reported upon by respondents. This attribute was initially included to ascertain if longer running projects had a greater benefit, or if there was a direct link between project duration and project cost. Upon reflection this attribute is very difficult to relate to direct benefit, there is also no direct link between duration of, and cost of projects, and in turn the attribute for duration of project is the most unreliable attribute to use to derive a value of the benefit of the use of the case study data within the project.

Therefore the attribute of cost of project is used as a measure to determine the benefit of the use of the case study data set within the rehabilitation and reconstruction community.

7.5.2 Quantifying benefit of use of case study data by project cost

If the case study data set had been used in the project the project managers were asked to state if the use of the case study data was critical (i.e. without the data the project would not run, or the project would not be effective) to the project, or if the use of the case study data just supported the operation of the project.

From the 23 respondents all projects had used the case study, with 52% of the respondents stating that its use was critical to the operation and successful completion of the project, inferring that the remaining 48% of respondents found that the use of the case study data set supported the completion of their project.

The total cost of projects directly supported by use of the case study data set is provided in Table 13.

Projects Using Case Study Data Set	**Total Project Cost[14]: Millions Euro**
Case study data set critical to project	24.29
Case study data set only supported operation of project	880.59
Total Cost of all supported projects	904.87

[13] BPS, SPAN 2005,

[14] Project costs were identified either as a total financial cost in United States Dollar, (USD), Indonesian Rupiah, (IDR), or Euro, or as a total effort in months. Exchange rates set as daily rate on 08-09-08, see www.xe.com. Only four projects provided project costs as effort. In these cases effort has been cost as 7,000 Euro per month effort (based upon follow up with the project manager, and based on a general average of technical and managerial staff cost)

Cost of project to provide case study data set	1.43[15]

Table 13 Summary of Costs of projects supported by Orthoimagery

7.5.3 Determination of benefit of the use of the case study data set based on cost to obtain same information

All respondents that had stated that the use of the case study data set was critical to the completion of their project were asked to estimate how much it would cost to obtain the same information they retrieved from the case study data set from another source.

The methods to derive the information ranged from traditional geodetic surveys, the acquisition of topographic maps, or through the acquisition and rectification of satellite imagery. The total estimated cost to derive the same information from other sources for the projects that deemed the use of the case study data set to be critical is provided in Table 14.

Case study data set critically supporting completion of projects	**Total Cost: Millions Euro**
Cost of project to provide case study data set	1.43
Cost to obtain same information from alternate source	3.46

Table 14 Cost to obtain same information

It must be clearly stated that Table 14 does not represent the cost of obtaining the same information as contained in the case study data set for the complete 6249 sq. km extent of the case study data set from alternate sources. Rather it just represents the cost of obtaining that information over the extents of the projects that reported they critically used the case study data set.

7.6 Orthophoto Constraints

A number of issues were highlighted in the use of the case study data set. There were a total of 16 constraints noted about the case study data from the 23 respondents. The main points, grouped into six categories, are highlighted in the following sections.

7.6.1 Availability of case study data:

Case study data set suffered from a long delivery time from image acquisition to availability within the rehabilitation and reconstruction community. This led to the data not being available for the project planning phase of projects starting before August 2006.

7.6.2 Data not up to date:

The case study data, acquired in June 2005, was out-of-date by the time it was delivered to the rehabilitation and reconstruction community. This was especially

[15] See section 3.3

noted given the quick developments in rehabilitation and reconstruction in tsunami affected areas

7.6.3 Coverage of Case Study Data:

There were a number of sections of Tsunami affected costal areas that were not included in the coverage of the case study data set.[16]

7.6.4 Spatial Accuracy of Case Study Data:

The case study data set did not meet the spatial (vertical or horizontal) accuracy specifications for all the projects that attempted to use the case study data set[17].

7.6.5 Visual Quality:

Minor sections of the case study data set were affected by cloud cover

7.6.6 Completeness of GIS data:

The TLM and data sets derived from the orthophotos were found not to be complete. This was especially true of the attribute information for the TLM data and the elevation information.

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[16] Some sections of Tsunami affected coastal areas that had been flown in the image capture campaign, were not given Military approval for release, see section 3.1.

[17] Noted only for projects requiring very detailing planning (i.e. 1,1,000 scale detailed engineering design for reconstruction of transport networks) – which was out the scope of the original project design of 1:10,000 scale mapping, see section 3.

8 Summary and Discussion

Of the 10 spatial data capture campaigns initiated as a direct response to the disaster wrought by the Tsunami, (reported in section 2.2), only 50% successfully saw the resulting spatial data being made freely available, at no cost and without restriction, to the rehabilitation and reconstruction community.

The NORAD funded orthophoto campaign was one of those successful projects. The project, titled the "Creation of an emergency GIS for the Rehabilitation and Reconstruction of Nanggroe Aceh Darussalam (NAD) and Northern Sumatera (SUMUT)", was completed in April 2006 and the spatial data generated by the project was provided to the SIM-Centre of the BRR, by Bakosurtanal in August 2006.From August 2006 to July 2008 the data set from the project was provided at no cost (by the SIM-Centre and by Bakosurtanal), to 99 projects within the rehabilitation and reconstruction community in NAD. These projects, with their own GIS and spatial data expertise, formed the primary users of this case study data set. The three main organisation types that requested use of the case study data set were the Government of Indonesia (37%), Non Governmental Organisations (27%) and the United Nations (14%). The four largest usage categories were for Urban or Rural Planning (48%), Environmental Protection (16%), General Project Planning (7%) and Transportation and Storage projects (6%).

Over 635 secondary users of the data set (i.e. those requesting only derived products) were identified. These included over 113 requests for large (A1) map products (>60%) to mainly GOI (43%) and NGO (50%) agencies. A large number (>400) of professional and semi professional spatial data users were exposed to the case study data set during GIS training courses.

The responses to a detailed questionnaire, distributed to the primary users of the case study data, show that the main users of the case study data were NGO (35%), GOI (26%) and IO (17%) agencies. The main projects using the case study data set were rural and urban development (52%), general environmental protection (22%) and transport and storage (13%) projects. Over 95% of the respondents used the case study data in the creation of maps which were used over 300 times, and 65% of the respondents integrated the case study data in a GIS.

The primary users of the case study data users reported that the case study data was most important for planning and operational phases of their projects, with approximately 90% of the primary users using the case study data in both of these project phases.

In this study the benefit of the use of the case study data set for disaster recovery has been quantified by using the attribute of the total cost of the projects supported by the use of the case study data. The case study data set, costing 1.43 million Euro to capture and provide to the rehabilitation and reconstruction community, critically supported the successful operation and completion of projects costing a total of over 24 million Euro, and provided support to a further 880 million Euro of projects.

For those projects which could not be successfully completed without use of the case study data set, it was estimated, as detailed in section 7.5.3, that it would have cost approximately 3.5 million euro to acquire the same information from alternate sources, such as from traditional geodetic survey or derived from satellite imagery. In addition to the extra costs, issues concerning the quality of alternative data, the timeliness of delivery, format, usability etc., come into question. It is very likely that alternative data sources would not be acceptable to the end user.

The timeliness of the delivery of the case study data to the rehabilitation community by Bakosurtanal, almost a year after the delivery of the imagery to Bakosurtanal by its contractor, as shown in Table 3, and nine months after the delivery of first completed section of orthorectified imagery by the contractor to Bakosurtanal, was noted as the main constraint in the use of the case study data set.

Due to the timeliness of its delivery, the case study data set was not available for many projects at their crucial project initiation stages. For example, the case study data was initially identified as being ideally suited for town planning for which, with over 6% of all provincial villages being damaged by the Tsunami, there was a clear and urgent need. This need was also reflected in the sectoral budget for reconstruction and rehabilitation of housing, being the largest of the 13 reconstruction sectors, representing some 26% of the 5.8 billion dollar reconstruction budget allocated by the end of 2006 Ref [2].

When the case data set was officially delivered by Bakosurtanal to the rehabilitation and reconstruction community in August 2006 over 44% of the 150,000 houses required, see Ref [7], had been completed and handed over to beneficiaries. At the same time a further 14,000 temporary houses and transitional shelters were in place, and the majority, Ref [8], of the remaining housing were in late planning stages. These projects completed or in progress at this time, either did not use any spatial data for co-ordination and planning, or, relied upon the use of the out of date 1978 topographic maps, which led to considerable confusion in coordination of activities within the BRR and reconstruction community.

Once the case study data was delivered to the rehabilitation and reconstruction community the case study data was found to be out of date for a number of reconstruction projects. By the time the case study data was made available, it reflected the ground conditions from at least 14 months earlier, meaning planning and coordination using the case study data was either based on data that did not reflect the current situation or that additional ground survey had to be undertaken to verify the actual current situation.

9 Conclusions and Lessons Learnt

The orthophoto case study data set was requested by 99 different projects across Nanggroe Aceh Darussalam during the period August 2006 to July 2008. The largest percentage of the data usage requests came from Government of Indonesia (GoI) and Non-governmental (NGO) agencies, with the main projects using the case study data set being rural and urban development and general environmental protection. Approximately 90% the primary users of the case study data found the case study data to be most important during planning and operational phases of their projects.

The study quantified the benefit of the use of the case study data set by determining if the use of the case study data set was critical to the successful completion of a project, or merely supported the project. Of the project attributes used to quantify the benefit of the use of the case study data set the project attribute that could most reliably verified, and therefore provide the most confident result, was found to be total project cost.

The use of earth observation data has been shown by this study to be of great benefit in disaster recovery. The case study data set critically supported projects worth over 16 times its actual cost and provided support to projects worth over 600 times its actual cost. Over 635 further secondary users of the case study data set were also clearly identified and their use of the data documented, but no attempt was made to assess the benefit of the use of the case study data to this user group.

The most commonly reported problem with the case study data was the late official delivery of the data to the reconstruction community. The delayed delivery of the case study data set to the recovery community meant that the case study data could not be used for sectors of reconstruction projects that had an urgent and timely need for completion. For example planning and coordination activities concerning housing, the major reconstruction activity in post Tsunami NAD, would have greatly benefited from the availability of the case study data set. Instead these projects either did not use any spatial data for co-ordination and planning, or, relied upon the use of the out of date 1978 topographic maps.

In order to determine and report upon the benefit of the use of EO data in disaster recovery, the following recommendations are offered:

- A robust, straightforward procedure must be in place with the EO data distributor that records simple criteria for each of the data users and related projects
- Disaster recovery projects are very dynamic in nature and the information about the projects changes over its lifetime, so the procedure must take into consideration the need to update the project information on a regular, but limited[18], basis
- The project information that the procedure records must be easily, and externally, verifiable

[18] i.e. project initiation and project closure

- All data user contact details must be confirmed and updated
- There must be a punitive measure in place to ensure that reporting is maintained by the data user throughout their projects lifetime
- Wherever possible international standards, such as the use of DAC5 code for project categorisation, should be included in the method

Whilst this report clearly shows that there is a need for the acquisition of EO data and the creation of spatial data in response to a disaster, a number of lessons have been learnt from the spatial data initiatives between Official Development Agencies (ODA's) and the GoI in response to the Tsunami in NAD. To ensure that the spatial data is used to its greatest benefit, it is specifically recommended that any spatial data campaign (undertaken with humanitarian funding), must also ensure the following, prior to the initiation of the campaign:

- A mechanism must be in place to ensure data is efficiently and effectively delivered to the humanitarian aid community in a timely manner;
- The mechanism must be open and accountable to data providers, donors and recovery community;
- The humanitarian aid and recovery community must have knowledge about the availability of the data;
- The spatial data must be freely accessible, either in terms of no cost, or low cost (i.e. data reproduction only), or in terms of unrestrictive licensing of data, to ensure the humanitarian aid budget is not wasted on the duplication of payment for the same data; and
- Ideally the mechanism should consist of a "one stop shop" i.e. a single point for data distribution and information about the data.

10 References

Ref [1]. Global Earth Observation System of Systems: 10-year implementation plan reference document. GEO 209pp, GEOSS, 2005.

Ref [2]. Aceh and Nias, Two Years After the Tsunami, 2006 Progress Report, BRR and partners, December 2006

Ref [3]. 2nd Tsunami Recovery Indicator Package (TRIP) Report for Aceh and Nias, UNORC- IAS October -December 2007

Ref [4]. Australia Indonesia Partnership for Reconstruction and Development (AIPRD) AusAID, Assessment of Priority Mapping Needs Nanggroe Aceh Darussalam and Nias Island, Northern Sumatra, 25th August 2006

Ref [5]. Master Plan for the Rehabilitation and reconstruction of the Regaions and Communities of the Province of Nanggroe Aceh Darussalam and the Islands of Nias, Province of North Sumatera, Ministry of National Development Planning (Bappenas), April 2005

Ref [6]. Final Report for creation of an emergency GIS for the Rehabilitation and Reconstruction of Nanggroe Aceh Darussalam (NAD) and Northern Sumatera (SUMUT), BLOM INFO A/S, June 2006

Ref [7]. Tsunami Recovery Indicators Package(TRIP) For Aceh And Nias, English Edition, UNORC-IAS, BRR, March 2007

Ref [8]. BRR PUSDATIN, August 2008, Pers Comms.

Ref [9]. IIASA Interim Report, IR-08-048, Banda Aceh - The Value of Earth Observation Data in Disaster Recovery and Reconstruction: A Case Study, 27 November 2008. On-line Report, http://www.iiasa.ac.at/Admin/PUB/Documents/IR-08-048.pdf

Annex A. Orthophoto Deliverables

The following tables record the deliverables provided under the project “Creation of an emergency GIS for the Rehabilitation and Reconstruction of Nanggroe Aceh Darussalam (NAD) and Northern Sumatera (SUMUT)” Ref [6].

Description	Deliverable Area	Quantity delivered
Aerial photography	6000 sq. km	6249 sq. km
DTM	6000 sq. km	6249 sq. km
50 cm. Orthophotos	5500 sq. km	5712 sq. km
25 cm. Orthophotos	500 sq. km	537 sq. km.
1:10000 line mapping	3000 sq. km	3015 sq. km
1:5000 line mapping	450 sq. km	450 sq. km

Table 15: NORAD Orthoimagery Deliverables

Delivery no:	Volume	delivered	accepted
# 1	1.000 digital images (500 RGB+500 CIR)	08/2005	15/08/2005
# 2.1 – 2.n	For every 500 set of RGB+CIR digital images up to 5.000 images (10 partial deliveries)	08/2005	16/08/2005
# 3	Remaining digital images, together with all GPS/INS data, results after AT	21/09/2005	21/09/2005
# 4	DTM and 50 cm orthophotos for at least 2500 sq. km (West Coast)	31/12/2005, 30/01/2006	09/02/2006
# 5	DTM and 50 cm orthophotos for at least 3000 sq.km (East Coast)	15/02/2006, 19/04/2006	25/04/2006
# 6	DTM and 25 cm orthophotos for at least 450 sq.km (Banda Aceh, Lamno)	29/09/2005, 16/11/2005	09/02/2006
# 7	Line mapping 1:10.000 for at least. 2.000 sq. km (East Coast)	25/04/2006	25/04/2006
Final	Line mapping 1:10.000 for at least. 1.000 sq. km (West Coast)	25/04/2006	25/04/2006
	Line mapping 1:5.000 for at least. 450 sq.km (Banda Aceh, Lamno)	22/03/2006	22/03/2006
	Emergency GIS hardware and software		17/05/2006

Table 16 Orthophoto Deliverables to Bakosurtanal

Annex B. Orthophoto Questionnaire

The following questionnaire (translated into Bahasa Indonesia and English) was distributed to all project managers who had been identified as the prime responsible data user in the orthophoto data user agreement signed between the data user and the Spatial Information & Mapping Centre, SIM-Centre, BRR NAD-Nias. The survey was implemented between July 2008 and September 2008.

Orthophoto Questionnaire

Please complete the following questionnaire and return to Richard A. Kidd, Senior GIS & Mapping Officer, Spatial Information & Mapping Centre, BRR NAD-Nias. Please return completed word document by e-mail to richard.a.kidd@gmail.com and copy (cc) sim.centre@brr.go.id

Please provide your contact details:

Name:	Please provide your name
Organisation:	Please provide the name of your organisation
E-mail:	Please provide your e-mail address
Phone:	Please your contact phone number
Date:	

Please answer the following 11 questions in the spaces provided. Responses can be entered in areas marked by the grey highlighted text.

Number	Question	Response
Qu. 1:	**Project Name:**	Please type your project name here
Qu. 2:	**Project Description:**	Please provide a brief overview of your project

	Total Project Beneficiaries:	------------------	Coverage of Project (km^2):	------------------	Project Duration (Months):	------------------
	Project Cost:	------------------		Unit (USD, IDR, Months Effort):		------------------
Qu. 3:	Did you use the data (aerial imagery, orthophoto) in the project:	Please Answer either Yes or No If YES please continue from Qu. 4: If NO please continue from Qu. 11:)				
Qu. 4:	During which phase of project was the data used:	Project Phase		Data Use and Importance Please state when the data was used and please rank response in order of importance: 1 most important, 5: least important		
		Project Initiation (i.e. proposal to donor, initial identification of potential project sites)		------------------		
		Project Planning (i.e. planning and refining project objectives i.e. site selection)		------------------		
		Project Operation (i.e. performing site surveying or land identification)		------------------		
		Project Monitoring & Evaluation (i.e. monitoring project progress)		------------------		
		Project Closure (i.e. final reporting)		------------------		
Qu. 5:	How was the majority of the data used in the project:	Creation, or use, of map products		Please Answer either Yes or No		
			How many times were the maps used		------------------	

		Creation of data sets (i.e. for use and integration in a GIS)		Please Answer either Yes or No	
			How many times were the data sets used		-------------------
Qu. 6:	**For each use of data, as noted in Qu. 4:, please briefly state (one or two sentences) how the data was used**	**Usage** **i.e. project planning: production of field survey documents, project closure: creation of maps to include in reporting to project donor)**		**Rank** **Please rank response in order of importance, most important first.**	
		-------------------		-------------------	
		-------------------		-------------------	
		-------------------		-------------------	
		-------------------		-------------------	
Qu. 7:	**Was the data critical to your project (i.e. without the data the project would not run, or the project would not be effective)**	Please Answer either Yes or No If YES please continue from Qu. 8: If NO please continue from Qu. 9:			
Qu. 8:	**If the data was critical to your project please estimate how much it would cost to obtain the same information from a different, or traditional, source (i.e. acquiring**	Please describe how the information would be obtained		------------------- ------------------- -------------------	

	the information from a geodetic field survey or purchase of data from other agency or provider)	Please provide an estimate the cost of obtaining the information for a different source (noting cost in either USD, IDR, or Months of Effort)	------------------- ------------------- Estimated Cost ___________
Qu. 9:	**Please note any problems or constraints of the data (i.e. data not spatially accurate, data difficult to visually interpret, data too old)**	Please note any data problems here	
Qu. 10:	**If not used, why was data not used in project?**	**Please select the most appropriate answer**	
		Original need for data not required	Please Answer either Yes or No
		Data too complicated to use	Please Answer either Yes or No
		Technical problem with data	Please Answer either Yes or No
		Data did not provide required information	Please Answer either Yes or No
Qu. 11:	**Have you provided written report on use of data to Spatial Information & Mapping Centre at BRR**	Please Answer either Yes or No	

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ORIGINAL PAPER

Implementation and integrated numerical modeling of a landslide early warning system: a pilot study in Colombia

Christian Huggel · Nikolay Khabarov · Michael Obersteiner · Juan Manuel Ramírez

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Abstract Landslide early warning systems (EWS) are an important tool to reduce landslide risks, especially where the potential for structural protection measures is limited. However, design, implementation, and successful operation of a landslide EWS is complex and has not been achieved in many cases. Critical problems are uncertainties related to landslide triggering conditions, successful implementation of emergency protocols, and the response of the local population. We describe here the recent implementation of a landslide EWS for the Combeima valley in Colombia, a region particularly affected by landslide hazards. As in many other cases, an insufficient basis of data (rainfall, soil measurements, landslide event record) and related uncertainties represent a difficult complication. To be able to better assess the influence of the different EWS components, we developed a numerical model that simulates the EWS in a simplified yet integrated way. The results show that the expected landslide-induced losses depend nearly exponentially on the errors in precipitation measurements. Stochastic optimization furthermore suggests an increasing adjustment of the rainfall landslide-triggering threshold for an increasing observation error. These modeling studies are a first step toward a more generic and integrated approach that bears important potential for substantial improvements in design and operation of a landslide EWS.

Keywords Landslides · Early warning systems · Earth observation · Uncertainties · Integrated modeling

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1 Introduction

Early warning systems (EWS) for natural hazards are important tools for disaster risk reduction. EWS have been developed for a number of different hazards, including tsunamis, volcanoes, snow avalanches, landslides, and others (Zschau and Küppers 2003). EWS commonly consist of different components, such as (i) sensors measuring geophysical, atmospheric, hydrodynamic, and soil-related parameters, (ii) telecommunication equipment transmitting the data to a (iii) monitoring and analysis center, (iv) decision procedures and organizational structures that facilitate the translation of the technical data into publicly understandable information, and (v) response of people, which may be affected. The awareness and knowledge of the people exposed to a hazard are very important for their adequate response to an early warning. As such, EWS have in fact increasingly been recognized as highly complex systems ultimately characterized by a tricky interaction between technical instruments and human behavior (Sorensen 2000; Basher 2006). Each EWS component has a certain potential for failure that determines whether the system eventually is successful or not. Due to the uncertainties related to the different procedures, a systematic evaluation of EWS is rather complicated.

We present here an approach to numerically model a landslide EWS that enables us to systematically assess the influence of the different EWS components on the overall performance and success of the system, including, for instance, climatically related changes, sensor related modifications, or changes in the human behavior.

We developed our model based on a recently installed landslide EWS in Colombia. Landslides are notorious in Colombia due to the rough topography and tropical rainfall conditions and thus are a major hazard in many regions of the country. The Combeima region, Tolima province, is a particularly exposed area, including several population centers along the valley and the regional capital Ibagué (ca. 0.5 million inhabitants). Hundreds of people have been killed by landslides and debris flows in the past. Most recently, multiple slope failures and landslides destroyed major parts of population centers in June 2006. These recurring events are therefore a serious threat to life, welfare, and local economy. So far, activities have mainly been focused on reconstruction after disasters, and prevention and preparedness activities have not been sufficiently developed. The landslide EWS has been designed and implemented within a Colombian-Swiss project funded by the Swiss Agency for Development and Cooperation (SDC) and is currently being calibrated and adjusted.

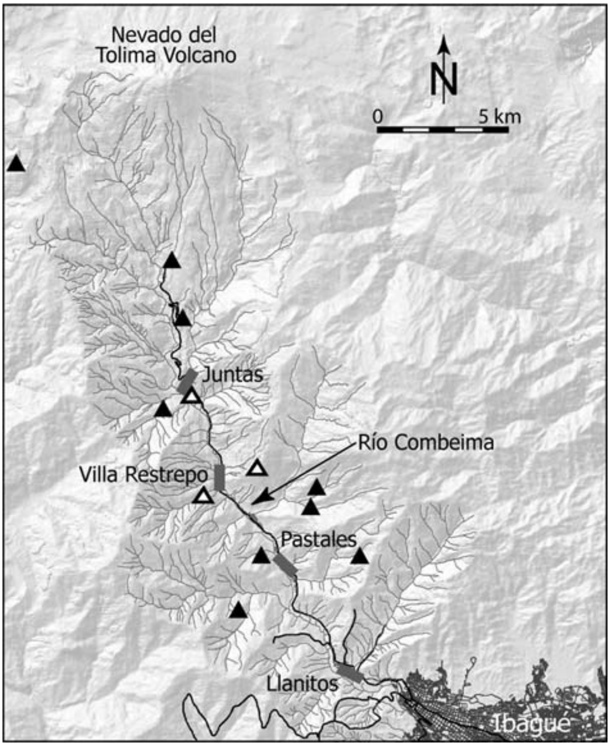
The integrated EWS model described in this article represents a novel approach and we therefore had to simplify several components of the real EWS. Nevertheless, it should be able to provide indications on how the EWS in the Combeima region could be improved in the future. Although the model is driven by data from this case study, the model concept is designed sufficiently open for adaptation to other landslide EWS.

2 EWS in Colombia

2.1 Study area

The Combeima river is one of the major drainages of the Nevado del Tolima Volcano, located in central Colombia in the Cordillera Central. The Combeima valley extends from the regional capital Ibagué (~500,000 inhabitants) at 1,250 m asl along more than 20 km to about 2,500 m asl before it abruptly rises to the summit of Nevado del Tolima at

Fig. 1 Map and stream flow system of the Combeima valley. *Triangles* indicate locations with rainfall stations (only partly operational), with *white triangles* referring to new telemetric rainfall stations that form part of the landslide EWS



5,200 m asl. Several towns populate the Combeima valley, with a total of about 5,500 people (Fig. 1). The area is characterized by very steep topography and dense vegetation. Mean annual rainfall varies between 1,500 and 2,500 mm. The geology is dominated by the volcanic activity of the area. Two major active volcanoes, Tolima and Machín volcano, are located within distances of 10 to 20 km and have repeatedly erupted during the Holocene (Thouret et al. 1995). As a consequence, the soils of the steep slopes of the Combeima valley are often characterized by a high content of ash and other volcanic products, partly with underlying metamorphic rocks. Geotechnical soil parameters are typically characterized by poor slope stability. Lahars and pyroclastic density currents from the Tolima volcano repeatedly swept through the valley during the past few thousand years, at least partly caused by interaction between volcanic activity and glacier ice on top of the volcano (Cepeda and Murcia 1988; Huggel et al. 2007).

Despite the steepness, the slopes are intensively cultivated in the lower sections by crops such as coffee, banana, maize, and others. Grazing by livestock is also widespread. Illegal burning of densely vegetated slopes for agricultural purposes is a serious problem, both in terms of uncontrolled forest fires and slope destabilization.

Steep topography, high rainfall intensities, and poor slope stability make the Combeima valley particularly vulnerable to landslides. In fact, people have suffered from landslide disasters for many decades (Godoy et al. 1997). Also, landslide events often occur in combination with flooding of the Combeima River with occasional process interaction such as blocking of the main river by landslide and debris flow material transported by tributaries. Figure 2 shows the chronology of landslide disasters in the Combeima valley for the last 50 years. Up to several hundred people were killed in single events, and damage to

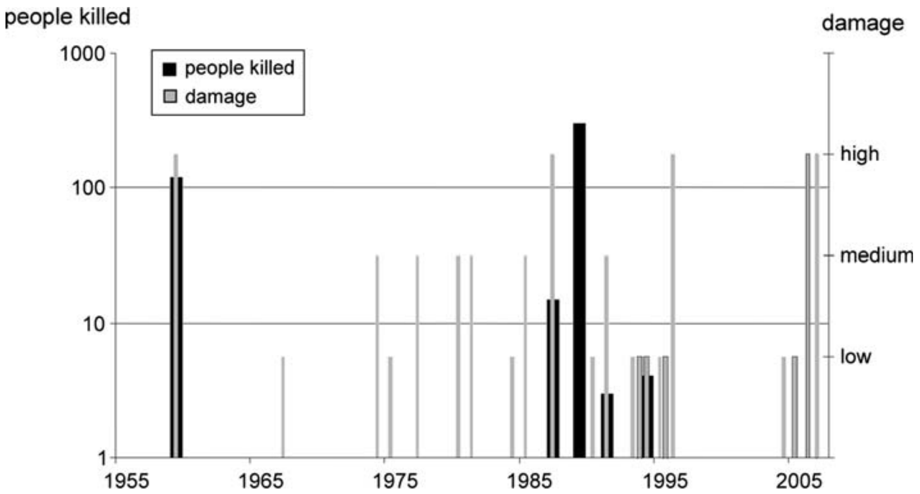


Fig. 2 Chronology of landslide disasters in the Combeima valley, distinguishing number of people killed and a qualitative measure of damage

residential areas and infrastructure has often been severe. The last major disaster occurred in June 2006, affected extended parts of the valley, and stroke the town of Villa Restrepo particularly hard (Fig. 3). In consideration of the magnitude and extent of the landslides and debris flows, it was very fortunate that no people were killed. Alerted by the sound of the rising tributaries, people could gather at safe places and avoid the violent impact of the debris flows.

2.2 Rainfall records

Rainfall measuring stations are a key component of a landslide EWS. In the Combeima valley, the first rainfall station was installed in the late 1950s. The bulk of stations existing today came into operation in the 1980s. Stations are operated by the Colombian Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) and data are centrally managed in Bogotá. The IDEAM network currently includes ten stations in the Combeima valley (Fig. 1). The rainfall recording is continuous on daily charts, which can be evaluated to intervals as low as 15 min. In January 2008, three telemetric stations were installed which can be programmed to transmit measured data when a rainfall increment occurs (i.e., 0.2 mm) or at a fixed time interval. Although the older rainfall gauges in the Combeima had a comparably high density, their use for a landslide EWS was limited because most of the stations are not telemetric and charts data are collected about every month. However, the data is valuable for ex post analysis of rainfall characteristics of the Combeima valley, and to relate rainfall to observed landslide events in the past.

For all stations, available rainfall records were analyzed, and rainfall intensities calculated based on 15-min recording intervals. This is a laborious work because several stations' data were not yet digitally stored and rainfall events had to be detected manually. Based on this analysis, rainfall intensity-duration frequency (IDF) curves per station were computed using SIAT, a specialized software tool (Ramírez 2007). For each rainfall station, the system reads the mass curve (time-accumulated rainfall) for every storm and computes intensities for user selected time periods (15, 30, 60, 120, 360 min). After

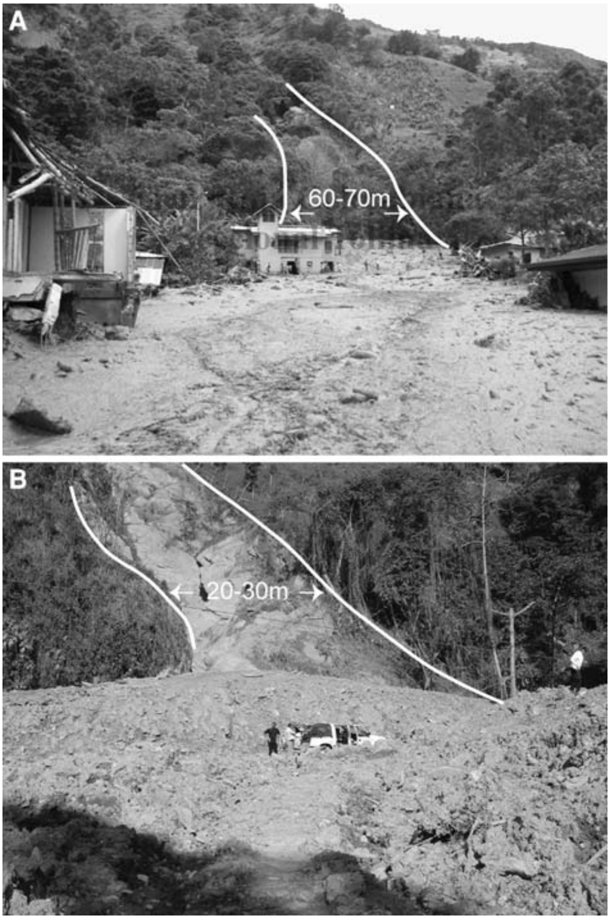


Fig. 3 Landslide disaster in the Combeima Valley in June 2006. **a** Devastated residential buildings in Villa Restrepo, and **b** debris flow channel and deposits obstructing the Combeima highway between Villa Restrepo and Juntas. Deposits height is in the order of 5 m (see car and persons for reference). The *solid lines* mark the trimlines of the debris flow channels and indicate the extremely large flow discharge. For the Villa Restrepo event, flow discharge is estimated at 300–400 m^3/s while normal discharge of the stream is less than 1 m^3/s (photos taken by **a** Colombian Red Cross and **b** C. Huggel)

reading all the storms for the station, the system defines for every time duration the maximum intensity for every year. Finally, a frequency distribution method is applied to obtain intensity-return period pairs for the given time duration.

The longest rainfall records for single stations were close to 20 years. Figure 4 shows two IDF curves for the stations "Placer" and "Palmar." They are located approximately at the same elevation of ~2,200 m asl but "Palmar" some 8.5 km up-valley toward Tolima Volcano. The analysis of the IDF curves suggests that the stations further downstream and further away from the Tolima Volcano have higher rainfall intensities. For instance, while the lower stations show a rainfall intensity of slightly less than 100 mm/h for a duration of 1 h and a 100-year return period, stations located further up-valley feature corresponding rainfall intensities reduced by ~30%.

Due to data limitations, it was not possible to relate IDF curves to observed landslide events to derive landslide-triggering rainfall thresholds (Glade et al. 2000; Guzzetti et al. 2008). However, daily rainfall data could be used to analyze antecedent rainfall conditions for a number of documented landslides. The about 20 landslide events on record often caused severe damage and destruction to local communities (Figs. 2, 3). Daily rainfall was analyzed up to 30 days prior to the landslide events, and for the station(s) closest to the

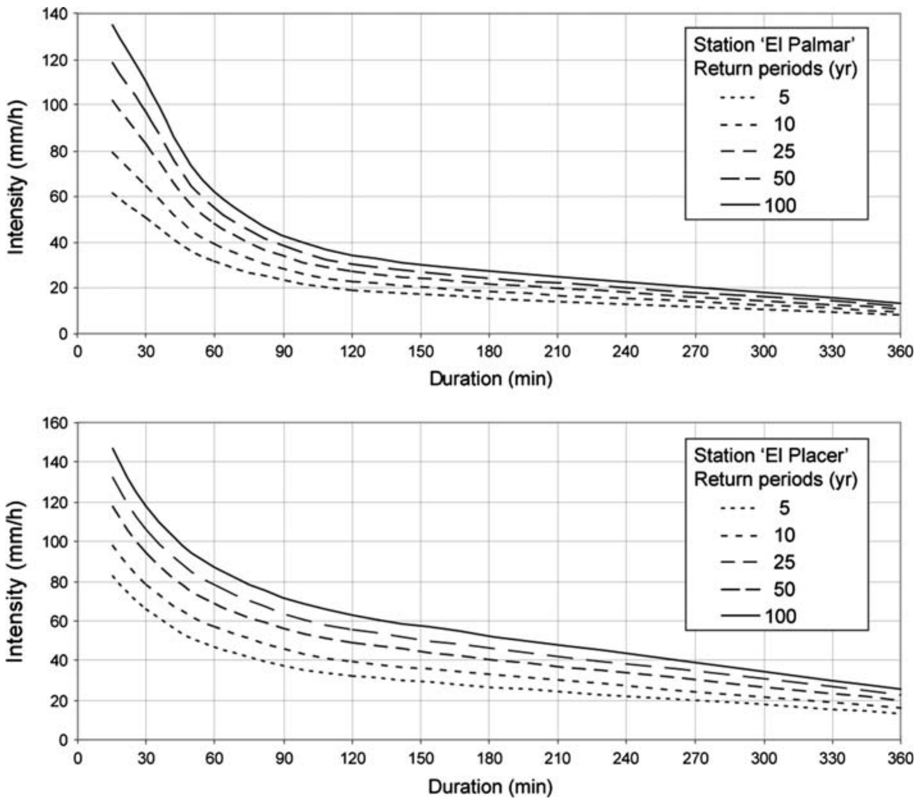


Fig. 4 Intensity-duration curves for rainfall stations "Placer" and "Palmar"

landslide initiation area. Figure 5 shows antecedent rainfall for all landslide events for which reasonably reliable relations to rainfall data could be established. The range of variability of landslide-triggering antecedent rainfall thresholds is considerable. As a first threshold indicator, 25-, 50-, 75-, and 90-quantiles of antecedent rainfall were calculated. In addition, the landslide records were evaluated in terms of their reliability of information provided, e.g., how precisely the landslide location could be identified, and the distance of the closest rain gauge to the landslide. Based on this, three classes of reliability of antecedent rainfall conditions (Fig. 5) were distinguished and helped to define warning levels for the EWS.

2.3 Implementation of EWS and related challenges

The magnitude and frequency of landslide disasters occurring in the Combeima valley have urgently called for an improved risk reduction. Structural protection measures are often not feasible due to financial restrictions. Organizational and preparedness measures such as EWS or emergency training have therefore been in the focus. Within a joint Colombian-Swiss Government project, the implementation of EWS has been a major objective.

However, the appropriate implementation and operation of a landslide EWS is a complex task and only few examples can be found worldwide. Probably, the earliest

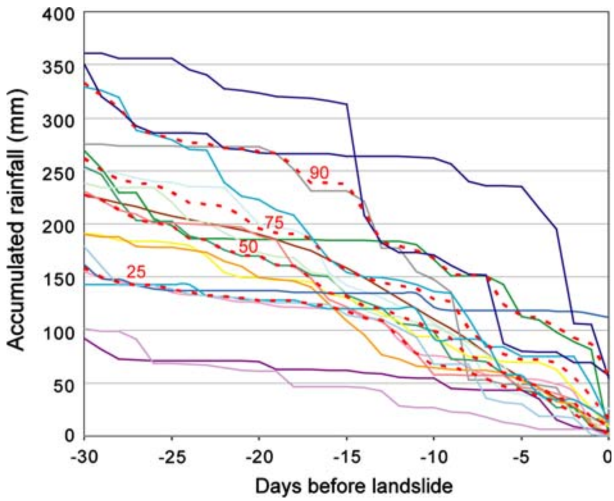


Fig. 5 Antecedent rainfall for documented landslide events between 1974 and 2006 in the Combeima valley. The graph shows the large variability of existing rainfall conditions triggering landslides. *Dashed lines* and corresponding numbers indicate 25, 50, 75, and 90% quantiles

landslide EWS was developed in the San Francisco Bay region (USA) in the mid-1980s and consisted of a real-time network of rain gauges, precipitation forecasts, and relations between rainfall and landslide initiation to define the alert level (Keefer et al. 1987). The relation between rainfall and landslide occurrence, or in more general terms, the understanding when, why, and how large landslides occur is an important basis for EWS. A number of physical models were developed that describe the mechanics of material strength, gravitational stress, pore-fluid pressure, and external forces (e.g., Iverson et al. 1997; Petley et al. 2005). A major drawback to apply physical–mechanical models for landslide EWS is the great variability of properties of soil and earth materials and slope conditions that make the prediction of when and where a landslide occurs very difficult. Therefore, empirical relations between rainfall duration or intensity and landslide initiation are typically applied for EWS. These relations need to be established by a record of landslide-triggering rainfall events. Several relations have been presented for different regions worldwide (Guzzetti et al. 2008), but are mostly lacking for Colombia so far (Terlien 1998). Due to the strong variability of rainfall and soil conditions, it is indispensable to develop a rainfall–landslide relation adapted to the region where the EWS is about to be implemented.

The spatial variability of rainfall and incomplete event description induce an uncertainty into the rainfall–landslide triggering threshold. It is essential that this uncertainty is adequately managed in EWS and efforts are put to reduce it. The need to improve the rainfall monitoring in the area by having automatic real-time rainfall gauges for EWS purposes gave reason to install three new rainfall gauges at sites located closer to the landslide initiation zones. The large variability of antecedent rainfall observed for past landslide events (Fig. 5) makes the definition of warning thresholds difficult. In a test phase of the EWS, quantiles were used to define increasing levels of landslide hazard. In order to further reduce the uncertainties, the rainfall stations were equipped with geophones that transmit increasing debris flow activity in the stream channels. A third control is achieved by local observers that report potentially landslide-producing situations timely to the EWS

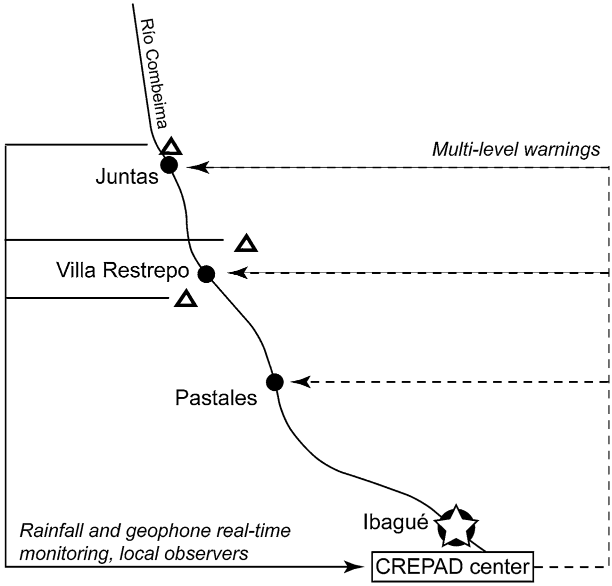


Fig. 6 Schematic structure of the landslide EWS in the Combeima region. *Triangles* denote recently installed rainfall and geophone monitoring stations. For the sake of clarity, not all local communities of the Combeima valley are included. CREPAD is the Regional Emergency Committee of Tolima

center in Ibagué (Fig. 6). At this center, which is hosted at the Regional Emergency Committee of Tolima (CREPAD), all available information is analyzed 24 h a day. Rainfall and geophone measurements are transmitted in real-time to an internet application and CREPAD operators or other potential users can directly consult with the internet to determine whether a rainfall–landslide threshold is reached. An emergency protocol defines the different levels of warning and the corresponding actions to be taken.

The EWS is only successful if it is also accepted, understood, and used by the local population. Even though the technical side of the EWS is complex, the greatest potential for failure exists if the local population is inadequately prepared for emergencies. Therefore, preparedness and social programs have been carried out in the Combeima region. These studies are, however, beyond the scope of this article, and will not be discussed here in further detail.

3 A numerical EWS model

3.1 Rationale for the approach

Design and implementation of the landslide EWS prompted a number of essential questions that are closely linked to the success of the system:

- What is the effect of errors in rainfall measurements on the reliability of a landslide EWS?
- How can uncertainties related to landslide-triggering rainfall thresholds be better handled in an operational EWS?
- How do the above points influence the impacts and consequences of landslide events?

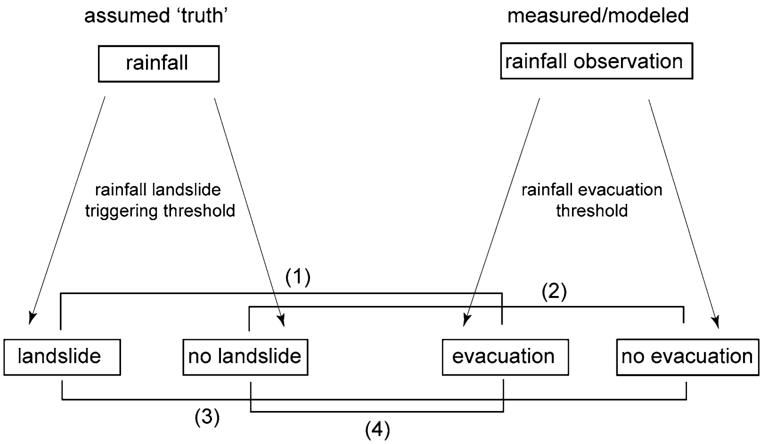


Fig. 7 Scheme demonstrating the essential components of the landslide EWS model. (1–4) represent four different scenarios for which damage estimates are calculated in the model: (1) damage to buildings and evacuation cost; (2) no cost; (3) damage to buildings and loss of lives; (4) evacuation cost

This may likely not be a complete list of essential questions related to the implementation and operation of a landslide EWS but it touches aspects of fundamental importance. These questions cannot definitely be answered by experience or by trial-and-error but need a more systematic approach. Here, we present a model based on a stochastic optimization approach, which is novel in its application for a landslide EWS. The model basically mimics different components of a landslide EWS, including the relations and criteria that link these components (Fig. 7). Obviously, the model requires several simplifications of the reality, which in our case, partly stem from limitations of the data. Methods, including the necessary simplifications, and applied data are presented in the following for each component of the model.

3.2 Observations: rainfall input data

Although there exists a rainfall record from several rain gauges in the Combeima valley (as outlined above), there are a number of limitations regarding complete data series over many years at temporal resolutions better than daily ones. Therefore, instead of local rain gauges, we used ERA-40 reanalysis rainfall data from the grid cell closest to the Combeima valley. ERA-40 is a reanalysis of meteorological observations from 1957 to 2002 produced and provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) in collaboration with other institutions (Uppala et al. 2005). The spatial resolution of ERA-40 data is 2.5°, and the center point of the grid cell used here is located about 60 km northeast of the Combeima valley. The temporal resolution of the rainfall data is 6 h.

It is clear that the rainfall conditions in the Combeima valley cannot be exactly represented by the ERA-40 reanalysis data but elevation and topographic conditions are similar. Furthermore, it has been observed that rainfall has a considerable variability even within the Combeima catchment. The use of a single point rain gauge data to be related to observed landslides over larger areas of the Combeima would therefore not be feasible. Due to these currently existing data restrictions, we refrained from directly verifying the ERA-40 reanalysis data with observed landslide events.

3.3 Intensity-duration threshold (LS—triggering)

Generally speaking, the landslide research has developed two different basic approaches to predict rainfall triggered landslides: physically based and empirically based models. Physically based models try to mimic the physical processes relevant to landslide initiation to determine landslide occurrence in space and time. Many physically based landslide models have been developed over the last years, and examples can be found, for instance, in Montgomery and Dietrich (1994), Iverson (2000), or Crosta and Frattini (2003). For use in EWS, a clear limitation of physically based models is the demand for detailed spatial information, including hydrological, lithological, morphological, and soil characteristics that control the initiation of landslides. These data are barely available over areas larger than specific test sites.

Empirically based models statistically relate rainfall parameters such as intensity and duration to observed landslide events. Rainfall intensity is commonly given in millimeters per hour and may be measured over shorter or longer periods, and correspondingly, has different physical implications (Wieczorek and Glade 2005; Guzzetti et al. 2007). Most commonly, the rainfall parameters intensity I (mm/h) and duration D (h) have been used to derive landslide-triggering thresholds based on observed events. Such thresholds have been developed for global (e.g., Caine 1980), regional (e.g., Larsen and Simon 1993) and local applications (e.g., Marchi et al. 2002). The threshold is usually expressed in the form:

$$I = aD^b \tag{1}$$

where a and b are empirical parameters.

Due to the limitations of physically based approaches for use in EWS, we implemented an empirically based threshold function in our model. We thereby consider a time period of 10 years split into smaller intervals of 6 h each. In the absence of any regional or local threshold available for our study region in Colombia, we used the Caine (1980) global threshold. The triggering threshold we used to model landslide occurrence is then described by a binary-valued function:

$$L(i) = \begin{cases} 1, & \text{if } \max\limits_{0 \le j \le 19} (I_{ij} - \tilde{I}_j) \ge 0, \\ 0, & \text{else.} \end{cases} \tag{2}$$

Here, $\tilde{I}_j = 14.82[6(j+1)]^{-0.39}, \quad j = 0, \ldots, 19$ are triggering intensities for time intervals ranging from 6 to 120 h, $i \ge 20$ is the number of a 6-h interval within the whole 10-year time period. Values $\{I_{ij}\}$ are calculated intensities: $I_{ij} = \frac{1}{6(j+1)} \sum_{k=0}^{j} r_{(i-k)}$ for rainfall data $\{r_i\}$. The value 1 of the function $L(i)$ represents a landslide occurrence in the ith time frame, whereas value 0 means no landslide in the ith time frame.

3.4 Observation errors and evacuation threshold

In (2), exact values of rainfall are used to calculate intensities I_{ij}. In reality, the exact precipitation is not known; instead, its value is measured with some error. In fact, quality and precision of measured rainfall data is a notorious problem for use in landslide models and early warning systems. We therefore intentionally introduced errors into the original ERA-40 rainfall data to assess corresponding effects on evacuation and damage. When simulations are run with degraded datasets of rainfall, the original ERA-40 data is taken as the control data, and it is assumed that the ERA-40 data perfectly represents the rainfall conditions at the local landslide site (Fig. 7).

We therefore model rainfall measurement error for each time frame i by means of random value generation distributed uniformly in the interval $[r_i - \varepsilon\, r_i,\ r_i + \varepsilon\, r_i]$ where ε is a constant rainfall measurement error with its value fixed in the interval [0, 0.3] for the purposes of numerical simulations.

Given exact rainfall information, one could use the threshold function (2) for evacuation. Here, for the sake of simplicity, we assume that upon reaching a triggering threshold in (2), an evacuation is performed within a "short enough" time frame, meaning before a landslide actually occurs. This assumption allows us to avoid substantial complications in the model related to rainfall forecasting. Taking into account rainfall measurement errors, a threshold for evacuation from a dangerous area should be adjusted. The idea is to decrease the original landslide-triggering threshold by multiplying it with the correction coefficient $\lambda \in (0, 1)$. The evacuation threshold function based on (2) is defined by the following expression

$$V(i,\lambda) = \begin{cases} 1, & \text{if } \max\limits_{0\leq j\leq 19}(\hat{I}_{ij} - \lambda\tilde{I}_j) \geq 0, \\ 0, & \text{else.} \end{cases} \tag{3}$$

where $\hat{I}_{ij}$ are intensities calculated for observed rainfall

$$\hat{r}_i \sim U(r_i - \varepsilon\, r_i,\ r_i + \varepsilon\, r_i), \tag{4}$$

where U denotes a uniform distribution within the specified interval.

3.5 Loss function

We define the loss function in the following form:

$$F(\lambda) = \sum_i L(i)[1 - V(i,\lambda)]d_i + L(i)b_i + V(i,\lambda)u \tag{5}$$

Here, $L(i)$ is defined in (2); $V(i,\ \lambda)$ is defined in (3); d_i is a random value describing the damage associated with loss of life incurred only in case if landslide occurs and no evacuation was performed; b_i is a random value describing the damage to the buildings and infrastructure; u is the cost of evacuation (constant value; Fig. 7). The loss function $F(\lambda)$ is a random variable depending on the evacuation threshold correction coefficient λ.

3.6 Optimization of evacuation threshold

The threshold for evacuation in the form (3) depends on adjustment coefficient $\lambda \in (0, 1)$, which is an unknown parameter subject to optimization. The objective of the optimization procedure is to minimize expected losses:

$$\min_{\lambda}\ \mathrm{E}[F(\lambda)] \tag{6}$$

Here, $\mathrm{E}[\cdot]$ denotes the expectation of a random value; the function $F(\lambda)$ is defined according to (5). An equivalent formulation of the optimization problem has the following form

$$\min_{\lambda} \sum_i L(i)[1 - V(i,\lambda)]\mathrm{E}[d_i] + V(i,\lambda)u \tag{7}$$

Here, we eliminated the constant $\sum L(i)\mathrm{E}[b_i]$ which does not depend on the adjustment coefficient λ. For the simplification purposes, we assume that there is no seasonal dependence of conditional (on landslide occurrence) expected loss of life induced by a landslide, and hence, can denote $\mathrm{E}[d_i] = v$ (fixed value). Based on that, the problem (7) may be represented in the form

$$\min_{\lambda} \sum_{i} L(i)[1 - V(i, \lambda)] + V(i, \lambda)\alpha, \quad \text{where } \alpha = \frac{u}{v}. \tag{8}$$

The problem (8) is equivalent to the original problem (6) in terms of optimal value of the adjustment coefficient λ.

4 Model results and sensitivity

In order to completely define the objective function in the optimization problem, it is necessary to define the damage associated with the loss of life and evacuation. For better reflecting reality, we introduce additional constraint on evacuation duration and require an evacuation period to be at least 24 h, meaning that if the value of $V(i, \lambda)$ defined in (3) would turn into 1 for a 6-h period i_0, then at least for the periods i_0, $i_0 + 1$, $i_0 + 2$, and $i_0 + 3$, the people would have been evacuated and would have been located somewhere outside of the dangerous area for that whole 24 h. After that period, if the intensities $\hat{I}_{ij}$ calculated for observed rainfall stay above the evacuation threshold as defined in (3), the people will not return back and will wait until the value $V(i, \lambda)$ drops to zero. We also assume that losses u do not incur per each 6-h interval of evacuation, yet per entire evacuation period (up to 5 days of consecutive series of threshold exceedance). Please note that Eqs. 5, 7, and 8 add sum u to losses per each 6-h interval of evacuation and therefore should be corrected. However, we will not introduce into equations the damage calculation rules verbally described above to avoid unnecessary complexity in formulas. This remark has to be kept in mind when we refer to the simplified Eqs. 5, 7, and 8.

We fixed evacuation cost $u = 10{,}000$ and expected loss of life (total per one landslide) $v = 5{,}000{,}000$ and calculated the expected losses for different values of adjustment parameter λ. These numbers can be considered in US Dollars and represent estimates for a typical situation in the Combeima valley. We simulated rainfall measurements during the period 1991–2000 based on ERA-40 data by introducing random errors according to (4). For values of rainfall measurement error ε in interval [0, 0.3] with step size equal to 0.05, we took 10,000 samples of simulated observations during the entire 10-year period. The results are presented in Fig. 8 (dots indicate minimum expected losses, i.e., optimal value of threshold adjustment). On a separate graph, we present the dependence of optimal expected losses on the rainfall measurement error (Fig. 9). It can be noted that errors in rainfall measurement lead to the exponential growth of expected losses. The dependence of the adjustment parameter λ, and thus the level of adjustment of the evacuation threshold, on the rainfall measurement error is presented in Fig. 10.

An important question connected with the optimization problem (8) is about the influence of a loosely defined constant α on the solution of the problem. We performed several model runs for various values of α and found out that to a certain degree, the optimal evacuation thresholds are insensitive to the values of α. Thus, Fig. 10, representing the decision making rule for evacuation, does not change if the cost of life v increases by 20%. This means that the evacuation thresholds for different levels of observation error and, most importantly, decision-making rules corresponding to the thresholds, are robust against a value, such as the cost of life that is difficult to define.

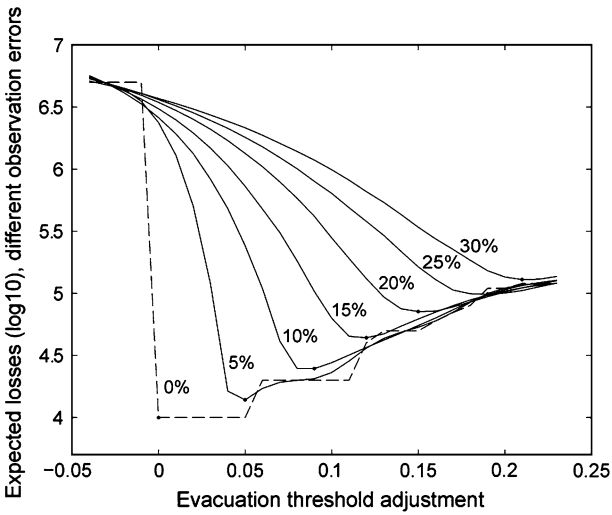


Fig. 8 Expected losses on log10 scale depending on evacuation threshold adjustment for different observation errors (0%, 5%, 10%,…, 30%). *Dots* on the graph indicate optimal values of adjustment, i.e., delivering minimal expected losses for given observation error

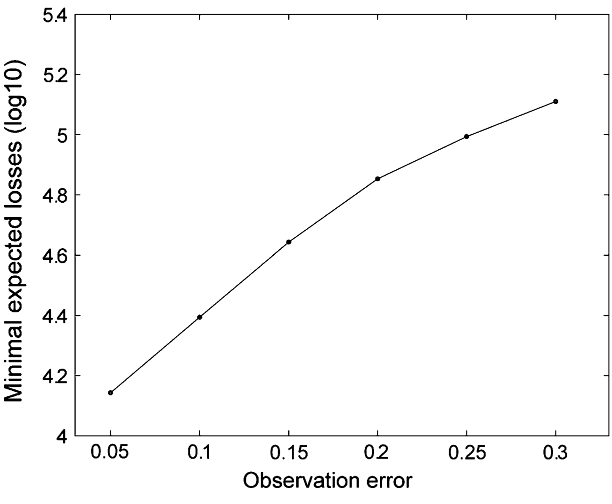


Fig. 9 Dependence of minimal expected losses (log10 scale) on the rainfall measurement error

5 Discussion and implications for landslide EWS

The approach developed in our model is based on stochastic optimization (Spall et al. 2006) with application to variable rainfall measurement errors and relevant evacuation thresholds, which has barely been applied to landslide problems so far. In landslide research, it is therefore rather uncommon to link measured environmental parameters such as rainfall with landslide consequences and damage in one integrated model. The approach has clear limitations but also significant potential that may lead well beyond what we have

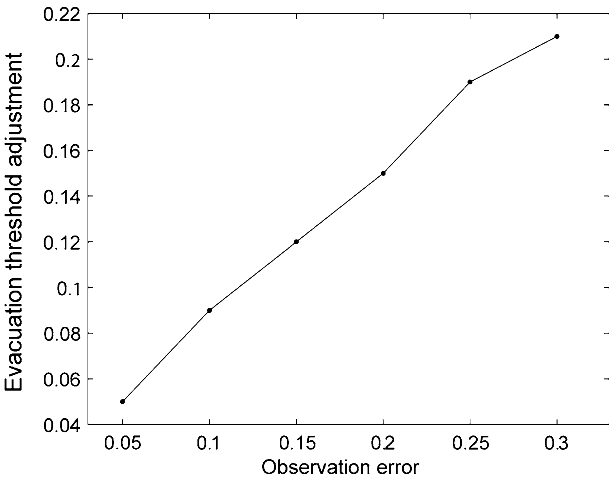


Fig. 10 Dependence of the evacuation threshold adjustment on the rainfall measurement error

presented here. The experience with first model development and simulations, and the implications for landslide research and risk management, is summarized in the following.

An integrated landslide EWS model of the kind presented in this study needs to make important simplifications to natural and human-based processes. Well aware of the current limitations in data and process understanding, we aimed at developing a model that has a basis in real world cases (Colombia) and at the same time provides an adequate theoretical background to allow for general conclusions on landslide EWS.

Rainfall observation errors are a very widespread problem in landslide EWS practice. The problem is serious because rainfall measurements are typically a core source of information for subsequent decisions on issuing warnings or ordering evacuation. The model results allow us to address the initially outlined research question on the effect of rainfall measurement errors on the extent of damage due to landslides. The results suggest that a linearly increasing observation error implies an exponentially rising loss due to landslides. These findings are also essential in the context of current initiatives in ground- and space-based earth observation (Fritz et al. 2008; Hong et al. 2006; Khabarov et al. 2008; Williamson et al. 2002).

In the presented model's setup, we use a deterministic intensity–duration landslide-triggering threshold. This relation was derived empirically with application of statistical methods based on the records of measured rainfall and registered landslide occurrence and hence includes related uncertainties. Therefore, randomization of the triggering threshold could potentially improve the model and bring it closer to reality. An implementation of a suitable approach to perform the threshold randomization based on reliable data could be a promising direction for future research.

An important question of practical relevance is whether the investment in more rainfall gauges would be worth, considering the potential benefit from loss reduction. Our model results can be an indication for such cost–benefit considerations. However, since the model is spatially not explicit, no answer is provided where the new gauges should be located to minimize the observation error. As the implementation of the EWS in the Combeima Valley has shown, there are several restrictions to find optimal sites for rainfall gauges. These include uncertainties in rainfall variation in space and time, extreme topography and access for maintenance, the acceptance by the local population, and problems with illegally armed groups. Realistic solutions usually imply a trade-off between such factors. In this context, the new findings from our model can be important for finding optimal investment solutions with government officials and donors in terms of effective disaster prevention.

Another important aspect evaluated in the model refers to the second research question, i.e., the importance of landslide-triggering rainfall thresholds for loss reduction. In our model, the decision on evacuation is solely based on the rainfall threshold. This is to some degree a simplification of the reality since an optimally designed landslide EWS should have a redundancy, e.g., local observers that report back to the EWS center, geophones, or additional sensors measuring parameters such as pore pressure in the soil, etc. However, to be able to provide straightforward conclusions on the effect of thresholds, we did not include any other parameters.

Our model indicates that to some degree, adverse effects by rainfall observation errors can be attenuated by adjusting the threshold. Systematic variation and optimization of the adjustment coefficient λ, based on 10,000 model simulations suggests that for a particular observation error and a threshold adjustment, a minimum expected loss can be found (Figs. 8, 10). The larger the observation error, the stronger should be the threshold adjustment. Results furthermore show that increasing the adjustment may have a negative impact in terms of expected losses.

These results are important for the design of evacuation decision-making procedures (Whitehead 2003). However, for a direct application to EWS practice, it should be considered that the model ignores any psychological "cost," i.e., evacuations in vain have only the relatively low cost in monetary terms. Increasing resistance by local population to evacuate with repeated evacuations without significant landslide events are thus not considered. In order to include this aspect in the model, more research is needed because people's response to warnings is generally complex. Dow and Cutter (1998), for instance, have shown that the likelihood of people responding to a warning is not reduced by the so-called "cry-wolf" syndrome if the basis of the false alarm is understood.

The values defined for the cost of evacuation (USD 10,000) and average total loss of life (USD 5 millions) are estimated for a typical situation in the Combeima valley, for a town potentially affected by a landslide. The number for loss of lives is based on a scenario of loss of 10 lives, where one life is set equal to USD 0.5 million. Defining a monetary value for life can be controversial from an ethical point of view but is a common practice in risk management for cost–benefit analyses of hazard protection and prevention measures. An advantage of our model in this context is that we were able to show that the adjustment of the evacuation threshold is to a certain degree not sensitive to the absolute value of loss of life.

An alternative approach to cost optimization would be the implementation of risk-based criterion such as cost minimization conditioned on admissible level of value-at-risk, where evacuation costs are strictly separated from loss of life instead of weighting loss of life in monetary terms. Moving into this direction and comparison with the present approach would be useful for better understanding the guiding principles the EWS should be based upon.

This study is a first step for an integrated numerical modeling of EWS that allow the investigation of aspects that have not been studied systematically so far. For future research in this field, we suggest the transformation to a spatially explicit model to study in more details the spatial aspects of EWS. Another step could be the introduction of the dependence of damage on landslide magnitude. Ideally, this should be based on magnitude–frequency relations of landslides which have gained substance with the analysis of quantitative landslide observations (e.g., Hovius et al. 1997; Crozier and Glade 1999). In principle, it has been found that the relation is a power law corresponding to the Gutenberg–Richter law for earthquakes (Dai and Lee 2001; Hungr et al. 2008). In order to establish an adequate relation for a particular region, a reasonable number of quantitative landslide observations is necessary. In this respect, a drawback for Colombia currently exists due to only few quantitative records available on landslide magnitude.

6 Conclusions

In many regions of the world, landslides cause billions of dollars of damage and often imply significant death rates (Keefer and Larsen 2007). Colombia is one of the particularly badly affected countries due to predominantly rugged terrain and tropical rainfall conditions. In many areas, landslide hazard zones overlap with residential zones and infrastructure. EWS are therefore important to reduce landslide risks, and in particular, avoid casualties. However, design, implementation, and successful operation of a landslide EWS is complex and has rarely been achieved. A critical problem is uncertainties related to landslide triggering conditions.

We have described here the recent implementation of a landslide EWS for a hotspot area in Colombia: the Combeima valley. As in many other cases, an insufficient basis of data (rainfall, soil measurements, landslide event record) and the aforementioned uncertainties represent an important complication. To be able to better assess the influence of the different EWS components, we developed a numerical model that simulates the EWS in a simplified yet integrated way.

Results show that a linearly increasing rainfall observation error implies a nearly exponential rise in damage cost. These considerations can help finding improved cost–benefit solutions for rainfall monitoring stations. We furthermore investigated uncertainties related to the rainfall landslide-triggering threshold, typically a key element for evacuation decisions. Stochastic optimization suggests an increasing adjustment of the threshold with increasing observation error. This essentially means that, in the future, not a fixed rainfall threshold would be used but rather one within a range of adjustment according to the local observation quality.

As we have seen with the practical EWS implementation in the Combeima valley, the success is also highly dependent on aspects such as institutional coordination, emergency protocols, or acceptance of the EWS by the local population. Nevertheless, our modeling studies are a first step toward a more generic and integrated approach that bears important potential for substantial improvements in design and operation of landslide EWS.

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References

Basher R (2006) Global early warning systems for natural hazards: systematic and people-centered. Philos Trans R Soc 364:2167–2187. doi:10.1098/rsta.2006.1819

Caine N (1980) The rainfall intensity-duration control of shallow landslides and debris flows. Geogr Ann A 62:23–27. doi:10.2307/520449
Cepeda H, Murcia LA (1988) Mapa Preliminar de Amenaza Volcanica Potential del Nevado del Tolima, Colombia, S.A., Informe 2070, 50 pp. INGEOMINAS, Ministerio de Minas y Energía, Informe 2070a
Crosta GB, Frattini P (2003) Distributed modelling of shallow landslides triggered by intense rainfall. Nat Hazards Earth Syst Sci 3(1–2):81–93
Crozier MJ, Glade T (1999) Frequency and magnitude of landsliding: fundamental research issues. Z Geomorphol 115:141–155
Dai FC, Lee CF (2001) Frequency–volume relation and prediction of rainfall-induced landslides. Eng Geol 59:253–266. doi:10.1016/S0013-7952(00)00077-6
Dow K, Cutter S (1998) Crying wolf: repeat responses to hurricane evacuation orders. Coast Manag 26:237–252. doi:10.1080/08920759809362356
Fritz S, Scholes RJ, Obersteiner M, Bouma J, Reyers BA (2008) Conceptual framework for assessing the benefits of a global earth observation system of systems. IEEE Syst J 2:338–348. doi:10.1109/JSYST.2008.926688
Glade T, Crozier M, Smith P (2000) Applying probability determination to refine landslide-triggering rainfall thresholds using an empirical "antecedent daily rainfall model". Pure Appl Geophys 157:1059–1079. doi:10.1007/s000240050017
Godoy BF, Guerrero MV, Hoyos C, Núñez TA (1997) Análisis de la vulnerabilidad de líneas vitales y edificaciones estratégicas en la zona rural de la cuenca del Río Combeima – Municipio de Ibagué, Tolima – Evento avalancha, detonante lluvia, 139 pp. Universidad del Tolima, Facultad de Ingeniería Forestal
Guzzetti F, Perucacci S, Rossi M, Stark CP (2007) The rainfall thresholds for the initiation of landslides in central and southern Europe. Meteorol Atmos Phys. doi:10.1007/s00703-007-0262-7
Guzzetti F, Perucacci S, Rossi M, Stark CP (2008) The rainfall intensity-duration control of shallow landslides and debris flows: an update. Landslides 5:3–17. doi:10.1007/s10346-007-0112-1
Hong Y, Adler R, Huffman G (2006) Evaluation of the potential of NASA multi-satellite precipitation analysis in global landslide hazard assessment. Geophys Res Lett 33:L22402. doi:10.1029/2006GL028010
Hovius N, Stark CP, Allen PA (1997) Sediment flux from a mountain belt derived by landslide mapping. Geol Soc Am 25:231–234. doi:10.1130/0091-7613(1997)025<0231:SFFAMB>2.3.CO;2
Huggel C, Ceballos JL, Ramírez J, Pulgarín B, Thouret JC (2007) Review and reassessment of hazards owing to volcano-ice interactions in Colombia. Ann Glaciol 45:128–136. doi:10.3189/172756407782282408
Hungr O, McDougall S, Wise M, Cullen M (2008) Magnitude–frequency relationships of debris flows and debris avalanches in relation to slope relief. Geomorphology 96:355–365. doi:10.1016/j.geomorph.2007.03.020
Iverson RM (2000) Landslide triggering by rain infiltration. Water Resour Res 36(7):1897–1910. doi:10.1029/2000WR900090
Iverson RM, Reid ME, LaHusen RG (1997) Debris-flow mobilization from landslides. Ann Rev Earth Planet Sci 25:85–138. doi:10.1146/annurev.earth.25.1.85
Keefer DK, Larsen MC (2007) Assessing landslide hazards. Science 316:1136–1138. doi:10.1126/science.1143308
Keefer DK, Wilson RC, Mark RK, Brabb EE, Brown WMIII, Ellen SD, Harp EL, Wieczorek GF, Alger CS, Zatkin RS (1987) Real-time landslide warning during heavy rainfall. Science 238:921–925. doi:10.1126/science.238.4829.921
Khabarov N, Moltchanova E, Obersteiner M (2008) Valuing weather observation systems for forest fire management. IEEE Syst J 2:349–357. doi:10.1109/JSYST.2008.925979
Larsen MC, Simon A (1993) A rainfall intensity-duration threshold for landslides in a humid-tropical environment, Puerto Rico. Geogr Ann A 75(1–2):13–23. doi:10.2307/521049
Marchi L, Arattano M, Deganutti AM (2002) Ten years of debris-flow monitoring in the Moscardo Torrent (Italian Alps). Geomorphology 46:1–17. doi:10.1016/S0169-555X(01)00162-3
Montgomery DR, Dietrich WE (1994) A physically based model for the topographic control of shallow landsliding. Water Resour Res 30(4):1153–1171. doi:10.1029/93WR02979
Petley DN, Higuchi T, Petley DJ, Bulmer MH, Carey J (2005) Development of progressive landslide failure in cohesive materials. Geology 33:201–204. doi:10.1130/G21147.1
Ramírez JM (2007) Sistema de información análisis de tormentas (SIAT). User Manual. Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM) Bogotá, 35 pp
Sorensen JH (2000) Hazard warning systems: review of 20 years of progress. Nat Hazards Rev 1(2):119–125. doi:10.1061/(ASCE)1527-6988(2000)1:2(119)

Spall JC, Hill SD, Stark DR (2006) Theoretical framework for comparing several stochastic optimization approaches. In: Calafiore G, Dabbene F (eds) Probabilistic and randomized methods for design under uncertainty. Springer, London, pp 99–117

Terlien MTJ (1998) The determination of statistical and deterministic hydrological landslide triggering thresholds. Environ Geol 35:124–130. doi:10.1007/s002540050299

Thouret J-C, Cantagrel JM, Robin C, Murcia A, Salinas R, Cepeda H (1995) Quaternary eruptive history and hazard-zone model at Nevado del Tolima and Cerro Machin volcanoes, Colombia. J Volcanol Geotherm Res 66:397–426. doi:10.1016/0377-0273(94)00073-P

Uppala SM et al (2005) The ERA-40 re-analysis. Q J R Meteorol Soc 131(612):2961–3012. doi:10.1256/qj.04.176

Whitehead JC (2003) One million dollars per mile? The opportunity costs of Hurricane evacuation. Ocean Coast 46(11–12):1069–1083. doi:10.1016/j.ocecoaman.2003.11.001

Wieczorek GF, Glade T (2005) Climatic factors influencing occurrence of debris flows. In: Jakob M, Hungr O (eds) Debris flow hazards and related phenomena. Springer, Berlin, Heidelberg, pp 325–362

Williamson RA, Hertzfeld HR, Cordes J, Logsdon JM (2002) The socioeconomic benefits of Earth science and applications research: reducing the risks and costs of natural disasters in the USA. Space Policy 18:57–65. doi:10.1016/S0265-9646(01)00057-1

Zschau J, Küppers AN (eds) (2003) Early warning systems for natural disaster reduction. Springer, Berlin, p 834

The Value of Observations for Reduction of Earthquake-Induced Loss of Life on a Global Scale

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Abstract – Earthquakes on global scale cause considerable losses both in terms of economic impact and human lives. A proper coordination of disaster response activities requires observation of affected areas for evaluation of spatial distribution of damage. We use several freely available datasets including global seismic hazard assessment, data on population, gross domestic product, and urban areas to calculate expected loss of life based on rescue efficiency derived from an optimal rescue resource distribution model, which by design includes the observation capacity as a parameter. Despite of the high practical importance, the quantification of the "observation quality – reduction of loss of life" relationship has not yet been performed for earthquakes on a global scale. Our validated quantitative results show that better Earth observations may potentially contribute to a global reduction of earthquake induced loss of life within the range 20% – 90% from the "business as usual" level.

Keywords: earthquake, Earth observations, disaster response, loss of life, global scale.

1. INTRODUCTION

Earthquakes cause substantial damage to infrastructure, economy, and human lives. Several catastrophic events during the past few years have sharply demonstrated the severity of earthquake consequences expressed particularly in human lives. According to the U.S. Geological Survey Historic Worldwide Earthquakes database, the earthquake in India, Gujarat dated 26 Jan 2001 has lead to more than 20 000 fatalities and more than 6 300 000 affected people; the earthquake in Pakistan, Bagh dated 8 Oct 2005 has caused more than 73 000 fatalities and more than 5 100 000 affected people; the earthquake in China, Sichuan dated 12 May 2008 has lead to more than 69 000 fatalities and more than 4 800 000 affected people. The statistics vividly shows how devastating and deadly an earthquake can be. Therefore, it is necessary to take all possible actions and better prepare to future earthquakes in order to reduce possible consequences especially in terms of loss of life.

1.1 Motivation

One of the major scientific problems regarding earthquakes is that according to the current state of the art it is impossible to reliably predict these disasters considerably in advance e.g. tens of minutes. This state of affairs does not allow the implementation of Early Warning Systems (EWS) providing enough time for safe evacuation of people from dangerous areas. In this paper we focus on the rescue operations in a few hours after an earthquake and study the dependence of the rescue resource distribution efficiency on the available amount of information about the damage incurred on the building stock. Basically, by knowing more precise information about the damage to the different parts of a city or region, one could better allocate rescuing resources necessary to save victims of an earthquake in the most affected areas.

1.2 Aims

Despite of the practical importance of improved information for disaster response, the quantification of the "observation quality – reduction of loss of life" relationship has not yet been performed for earthquakes on a global scale. Our aim is to develop a model that would allow for a quantitative global assessment of the value of improved observations for disaster response to earthquakes. More specifically, we aim at obtaining quantitative results measuring the feasible reduction of earthquake induced loss of life on a global scale that better Earth observations (EO) could contribute to. For that purpose we perform an assessment of the potential of the expected decrease having "business as usual" as a baseline. Additional sub-goal is to validate the model on a regional scale in several case studies to explore if there is an agreement between globally-derived predictions and the real-case data reported from the field. In this paper we do not specify the way of obtaining the EO data in order to avoid inessential constraints and leave enough space for all possible implementations and relevant methods. The research presented here is focused on post-disaster actions aimed at saving lives of the earthquake victims. The ex ante actions and reduction of economic loss are beyond the scope of this paper.

1.3 References to Related Work

The importance of rapid earthquake damage assessment and some real applications are presented in e.g. Midorikawa and Abe (2000). The application of earthquake warning systems providing very short warning times to secure potentially dangerous objects in Japan is presented in Meguro (2005). The papers presenting the empirically derived interdependence between technical characteristics of an earthquake as well as expected damage on different measurement scales include such early works as Ambraseys (1973) and more recent papers as by Karim and Yamazaki (2002). An overview of empirical methods and assessment techniques as well as earthquake engineering practices is presented in Seligson and Shoaf (2003).

1.4 Overview

The rest of the paper is organized as follows: section 2 presents the model and basic datasets. Section 3 presents both results of the global assessment as well as some regional case studies used for validation of the model. Section 4 draws up the conclusions.

2. MODEL AND DATA

An important part of the model is the functional dependence of rescue efficiency on available observations, rescue resources, and damage caused by an earthquake to the buildings. The rescue efficiency is defined as follows:

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$$rescue\ efficiency = \frac{number\ of\ saved\ victims}{total\ number\ of\ victims}. \tag{1}$$

Here under the "total number of victims" we assume the people who were not immediately killed by an earthquake and who could be potentially saved by providing timely medical treatment. We model the rescue efficiency based on the stochastic simulation approach. We assume that a city (or a region affected by an earthquake) is divided into N blocks (or sub-regions) and there are n houses in each of those blocks. We assume that the probability of a house to collapse during an earthquake is p. So, the number of collapsed buildings in the i^{th} block is a binomially distributed random variable $x_i \sim \mathrm{Bin}(n, p)$. Let's assume that the number of rescue brigades is limited to R and that one brigade can rescue the victims from one collapsed building. The problem of optimal resource distribution consists in maximization of the overall rescue efficiency by assigning certain number of rescue brigades r_i to each of the blocks (i=1,…,N) under the given resource limitation R. According to (1) this leads to the following calculation formula:

$$rescue\ efficiency = \begin{cases} \dfrac{\sum_{i=1}^{N} \min(x_i, r_i)}{\sum_{i=1}^{N} x_i}, & \sum_{i=1}^{N} x_i \neq 0, \\ 1, & \sum_{i=1}^{N} x_i = 0. \end{cases} \tag{2}$$

Here we used the number of collapsed houses as a proxy for the number of victims in need of rescue. This assumption is reasonable if all the houses have similar construction and have equal number of inhabitants, so that the average number of victims per house shows up both in the numerator and the denominator and cancels out. The minimum function in the numerator reflects the fact that a rescue brigade cannot save more victims than actually available in the i^{th} block. A parameter describing observation capacity can naturally be included into the earthquake aftermath rescue efficiency model presented above. One can imagine that the information about the damage from the i^{th} block may not be available. Let denote by K the number of blocks with the known information about the damage – known value of x_i. The quality of observation may be expressed as the ratio of the number of blocks with known damage information to the total number of blocks:

$$quality\ of\ observations = \frac{K}{N}. \tag{3}$$

There could be different reasons why $K \neq N$. For instance, if the observation system used for the purposes of damage assessment is based on satellite imagery, some parts of the affected area could be obscured by clouds so that no information could be obtained for those parts. The earthquake rescue efficiency estimation model presented above includes resource constraint R as an important parameter. This parameter can describe the availability of trained staff and special rescue equipment, the proximity to hospitals and their respective capacity, and many other relevant factors. For the sake of simplification we assume that the amount of rescue resources is initially sufficient to save all the victims of an earthquake. This assumption might seem over-optimistic, since many earthquake reports show the lack of rescue resources especially in case of large earthquakes. Taking that into account, we make an alternative "pessimistic" assumption about the vulnerability of the rescue resources to the earthquake, namely, that the amount of available rescue resources decreases with the increasing probability of collapse, so we use (1-p)R instead of R for this case. Based on those two "optimistic" and "pessimistic" assumptions we get two assessments of the rescue efficiency for each value of p and also for the two values of quality of observations (perfect observations and no observations). By running the Monte-Carlo simulations of the model described above, we estimate the dependence of the rescue efficiency on quality of observations and probability of collapse p. The results of this modeling* are illustrated on the Figure 1.

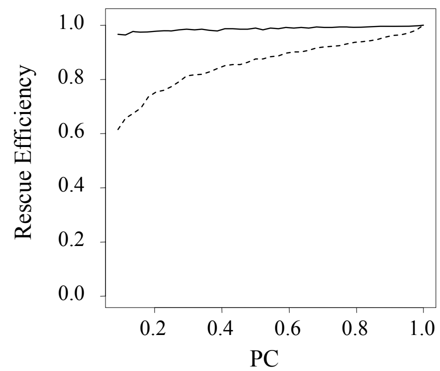

Figure 1. Rescue efficiency depending on probability of collapse (PC), "non-vulnerable" resources (dashed line – without observations, solid line – with observations).

2.1 Global Datasets

The model uses four global datasets describing spatial distribution of population, urban extents, gross domestic product (GDP), and global seismic hazard. The datasets have different spatial resolution, so that some preliminary steps as rescaling and unifying of coordinate systems are needed to operate them on the same scale. As a part of the model input, we use the global population and urban extent data provided by CIESIN (2004a and 2004b). The assumption on the buildings' type in the grid cell and their probabilities of collapse in case of an earthquake are based on those datasets. The assessment of GDP per capita was calculated based on population projection for 2025 provided by CIESIN (2002a) and downscaled projection of GDP for 2025 made by CIESIN (2002b). This indicator was used in the model to classify grid cells into 'rich' and 'poor' classes. For the purposes of the earthquake hazard assessment we used the global seismic hazard map GSHAP (2000).

2.2 Modeling Damage and Loss of Life

The global earthquake damage assessment model is based on the global datasets described above and the application of thresholds for distinguishing between urban/rural and 'rich/poor' areas, probability of collapse estimation, and rescue efficiency assessment based on the quality of EO as defined in (3). For the purposes of the damage modeling we use the intensity scale developed by the Japan Meteorological Agency (JMA). The

* The modeling of the earthquake rescue efficiency was performed together with Elena Moltchanova from the National Public Health Institute, Helsinki, Finland.

probability of collapse, which is at the core of the model, is calculated according to the Table A. The JMA intensity – PGA relationship we used for conversion is described by the formula

$$\log_{10}(PGA) = 0.5\, I_{JMA} - 0.347 \tag{4}$$

according to Ambraseys (1973) which is quite similar to the relationship presented in the more recent paper by Karim and Yamazaki (2002), yet seems to be more relevant on global scale as compared to the modern adjustments of JMA scale. The values in the Table A are suggested to quantify the official verbal descriptions of the JMA intensity.

Table A. Probability of collapse depending on building type and JMA intensity.

JMA intensity (PGA, m/s^2) / Building type	**5.5 (>2.5)**	**6.0 (>4.5)**	**6.5 (>8.0)**
Wooden, poor	0.25	0.5	0.75
Wooden, resistant	0	0.1	0.25
Concrete, poor	0	0.25	0.5
Concrete, resistant	0	0.1	0.25

After calculating the probability of collapse, the expected number of mortalities *EM* per grid cell is calculated using the formula

$$EM = POP \times PC \times PV \times (ID + SR \times RE), \tag{5}$$

where *POP* is the population in the grid cell, *PC* is the probability of collapse depending on PGA according to the Table A, *PV* is the ratio of the seriously injured victims conditional on collapse, *ID* is the ratio of the victims (out of seriously injured) who immediately die because of the severity of the earthquake-caused traumas, *SR* is the ratio of seriously injured victims who are subject to rescue, so that $ID + SR = 1$ by definition. *RE* is the rescue efficiency as defined in (2). According to the estimates suggested by Seligson and Shoaf (2003), in our model *PV*=0.30 and *SR*=0.67.

3. RESULTS

The model is able to calculate the earthquake-caused mortalities estimation on different scales. Below we present the global assessment and also several assessments for regional-scale case studies.

3.1 Global Assessment

We applied our model on the global scale and compared the assessment with the historical data over the last 30 years to evaluate the performance of the model. The benchmarking period is 1980-2008. The calculation methodology for the estimation of the earthquake-caused mortalities on the global scale implemented in the model delivers quite satisfactory results presented in the Table B, where for reported mortality statistics we used the data according to the EM-DAT database (the OFDA/CRED International Disaster Database, Université catholique de Louvain, Brussels, Belgium) for the period 1980-2008 (April). Modeled data are rescaled back to 1980-2008 and adjusted to population for comparison purposes. The upper and lower assessment values correspond to non-vulnerable and vulnerable resources. After the application of the PGA threshold presented by the GSHAP map and calculating the expected number of mortalities *EM* as described above, we apply the following scaling coefficients:

$$EM_{rescaled} = EM \times (GP_{1980} + GP_{2008})/2/GP_{2000} \times 0.1 \times 28/50\,.$$

Here, GP_{1980} and GP_{2000} are population for 1980, 2000, and GP_{2008} is a projection for 2008 according to the U.S. Census Bureau (2008). The probability 0.1 of PGA threshold exceedance during 50 years (provided by GSHAP) is rescaled to calculate the estimation within a 28 years time period. We assume that only a 500-year event, i.e. the PGA value exceeding GSHAP threshold, may cause a substantial damage, implicitly reflecting by this the local building practices, which should normally take into account local seismic conditions.

Table B. Global assessment of earthquake caused mortalities for the period of 1980-2008 (reported mortalities are according to the EM-DAT database for the period 1980 – April 2008).

	Reported mortality statistics	Non-vulnerable resources	Vulnerable resources
Without EO	300 000	297 000	582 000
With EO		29 000	447 000
Relative reduction:		90%	23%

The data reported by the statistics is quite well within the lower and upper bounds of the model's predictions taking into account the data on the China's Sichuan earthquake (12 of May 2008, 69 000 mortalities reported). The results presented in the Table B, show the importance of observations and the substantial potential for their use in reducing the number of fatalities on a global scale. However, the effect of using this vitally important information is limited by the available amount of rescue resources (trained personal and necessary equipment), which is reflected by the column "Vulnerable resources". The promising first results from the model presented in Table B cannot be used alone as a proof of the validity of the predictions, since Table B compares the average result of some distribution with only one sample value. Nonetheless, Table B provides useful information on the performance of the model under current assumptions and presents the potential benefits of EO.

3.2 Case Studies

For the purposes of the model validation on a smaller (regional) scale, we performed several case studies, for which the PGA maps and mortality statistics are available. Above we mentioned thresholds used to classify grid cells into classes for the purposes of the earthquake damage estimation. In the following case studies we use an additional threshold. Now we have two PGA datasets available to us – one is the GSHAP map (as we used it before), and the other is the real PGA map corresponding to the respective event. The reason for using GSHAP data, even in case when real data exist, is to be able to reflect the preparedness of each particular area to an event of certain magnitude. Since GSHAP reflects the magnitude of a 500-year event, we assume that buildings in the corresponding areas are well prepared and resistant to the earthquakes of smaller magnitude. The case studies presented below include the following earthquakes: Iwate earthquake (Eastern Honshu, Japan, 14.06.2008), Great Sichuan earthquake (Sichuan province, China, 12.05.2008), Kashmir earthquake (Kashmir, Pakistan, 8.10.2005), Gujarat earthquake (Gujarat, India, 26.01.2001), Loma Prieta earthquake (California, USA, 17.10.1989), San Fernando earthquake (California, USA, 09.02.1971). The results are summarized in the Table C, where we see that for the earthquakes in the USA and Japan the model gives good low assessments, with slight underestimations for Iwate and San Fernando, whereas the lower and upper estimations (VR+/-) for the EO scenario (EO+) for Loma Prieta earthquake provide good approximation of the reported fatalities. For larger earthquakes we see a reasonable approximation for Sichuan and Gujarat (both reported values are within the upper and lower boundaries for EO+ and EO–).

Table C. Performance of the model for the case studies when not using EO (EO–) and using EO (EO+) for non-vulnerable (VR–) and vulnerable (VR+) rescue resources (10^3 fatalities).

Earthquake	Mortalities Reported	EO–		EO+	
		VR–	VR+	VR–	VR+
Iwate	0.012	0	0	0	0
Great Sichuan	> 69	65	269	8.6	257
Kashmir	> 86	15	41	1.8	37
Gujarat	> 20	13	32	1.4	28
Loma Prieta	0.063	0.65	0.7	0.03	0.16
San Fernando	0.065	0	0	0	0

In the Kashmir case-study area, the model reported an underestimated assessment, which is most probably due to considerable number of strong aftershocks having cumulative destructive impact on the area as reported by Naeem et al. (2007). This disagreement with the reported numbers is not a flaw of the model because the main dataset of the model (GSHAP) does not contain any earthquake aftershock/duration-related information. Generally speaking, the case studies demonstrate reasonable performance of the global modeling approach even for the assessment of particular regional-scale events.

4. CONCLUSION

In this paper we presented an assessment tool to quantify the value of improved Earth observations to reduce human fatalities resulting from earthquakes. We purposely tried to keep the global model as simple and transparent as possible. The series of simplifying assumptions we made was necessary to make the model applicable to the available datasets. The suggested model leaves wide open space for possible improvements e.g. better resource constraints, stochastic modeling of an earthquake occurrence, etc., defining directions to go next. The highly aggregated and simplified global earthquake damage assessment framework described in our paper is quite transparent, yet it explicitly includes the naturally defined quality of Earth observations as a parameter and demonstrates the way of quantitative assessment of the importance of those observations. We validated the model on a regional scale in several case studies and found a good agreement of global predictions with the data reported from the field. However, the adjustments to the model for using more precise relevant local data and improving its estimations seem to be a challenging direction for further research. We anticipate this paper to be a starting point for more sophisticated models for measuring the earthquake-related value of information.

REFERENCES

N. N. Ambraseys, Notes on Engineering Seismology, Engeneering Seismology and Earthquake Engineering, edited by J. Solnes, NATO Advanced Study Institute Series, Series E: Applied Sciences – No. 3, 1973.

Center for International Earth Science Information Network (CIESIN), Columbia University, Country-level Population and Downscaled Projections based on the B2 Scenario, 1990-2100. Palisades, NY, 2002a. http://www.ciesin.columbia.edu/datasets/ /downscaled

CIESIN, Columbia University, Country-level GDP and Down-scaled Projections based on the A1, A2, B1, and B2 Marker Scenarios, 1990-2100. Palisades, NY, 2002b. http://www.cie-sin.columbia.edu/ datasets/downscaled

CIESIN, Columbia University, Global Rural-Urban Mapping Project (GRUMP): Urban/Rural Population Grids. Palisades, NY, 2004a. http://sedac.ciesin.columbia.edu/gpw/

CIESIN, Columbia University, Global Rural-Urban Mapping Project (GRUMP): Urban/Rural Extents. Palisades, NY, 2004b. http://sedac.ciesin.columbia.edu/gpw/

GSHAP, The GSHAP global seismic hazard map. The Global Seismic Hazard Assessment Program, 2000. http://www.sei-smo.ethz.ch/GSHAP/global/

K. R. Karim and F. Yamazaki, Correlation of JMA instrumental seismic intensity with strong motion parameters, Earthquake Engng Struct. Dyn. 2002; 31:1191–1212 (DOI: 10.1002/eqe.158).

S. Midorikawa, S. Abe, Real-Time Assessment of Earthquake Disaster in Yokohama based on dense strong-motion network, 12WCEE, Paper 1036, 2000.

A. Naeem, Q. Ali, M. Javed, Z. Hussain, A. Naseer, S. Muhammad Ali, I. Ahmed, and M. Ashraf, A Summary Report on Muzaffarabad Earthquake, Pakistan, Earthquake Engineering Center at the Department of Civil Engineering, University of Engineering and Technology, Peshawar, Pakistan, 2007.

H. A. Seligson, K. I. Shoaf, Human Impacts of Earthquakes, in the Earthquake engineering handbook, by Wai-Fah Chen, and Charles Scawthorn (editors), CRC Press, 2003.

U.S. Census Bureau, Population Division, World Population: 1950-2050, International Data Base, July 2008 Update. http://www.census.gov/ipc/www/img/worldpop.gif

Optimal Forest Management with Stochastic Prices & Endogenous Fire Risk**

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Abstract – Earth observations are one way to reduce the risk to standing forests from damages caused by wild fires, since they enable early warning systems, preventive actions and faster extinguishing of fires, before they spread out. Another channel through which fire hazard can be reduced is the thinning of the forest, so the risk of a fire occurring becomes partially endogenous. In order to shed more light on optimal forest management under such endogenous fire risk, we develop a real options model, where the price of biomass is stochastic and the harvesting decision needs to be timed optimally in the face of these uncertainties. We find that there is a positive value of information. In other words, there is a positive willingness to pay for Earth observations by forest managers.

Keywords: value of information; Earth observation; endogenous risk; real options

1. INTRODUCTION

The recent upsurge in large-scale wild fires as for example in Austria has raised the public's awareness of the need to establish mechanisms to accelerate fire extinguishing, evacuation and – if possible – the prevention of the fire in the first place. However, such mechanisms are useless, if there is not sufficient information about the incidence and location of the fires. Khabarov, Moltchanova and Obersteiner (2008) conduct simulation studies to estimate the benefits of a finer grid of weather stations and more frequent patrols in forest areas, so that wild fires can be detected earlier and – if not prevented – at least limited or extinguished before they can spread to a larger area and thus cause economic damage and endanger the life of humans and animals. They find that the addition of more weather stations indeed reduces the fraction of the area burnt by wild fires. The value of Earth observations is thus substantial for the information of wild fire containment activities and will have decisive influence on forest management issues such as optimal rotations.

1.1 Motivation

The forest sector is characterized by irreversible decision-making (the cutting of trees) under uncertainty (the risk of fire and the price of biomass). The problem setup therefore qualifies for the application of real options theory (Dixit & Pindyck, 1994). The main idea behind real options is that sufficiently large uncertainty makes it worthwhile to postpone irreversible decisions. In the case of forestry management, the decision to cut trees will be postponed until more information about the price that can be earned by selling the wood becomes available. In other words, the option to cut has a "waiting" value, which initially exceeds the immediate profits from cutting and selling trees. The real options approach then enables the determination of the optimal timing of this decision.

The other source of uncertainty we want to consider and actually focus upon in this study is fire hazard and the potential impact of Earth observations in this context. In fact, if the incidence of fire can be reduced due to quick extinguishing or even prevention actions, then this will have substantial impacts on profits and – as will be shown in the analysis – behavioral patterns will change as well.

In this paper we model fire risk to be increasing in stand age, which is of course dependent on the rotation decisions. The fire risk is therefore partially endogenous to the optimization of the forest manager's behavior, as will be seen in the results. The analysis is thus not only useful to evaluate the benefits from Earth observation, but it is also interesting from the theoretical point-of-view: González Olabarria (2006), for example, finds in his doctoral thesis that an increase in fire risk leads to shorter rotations if fire risk is purely exogenous. If the risk is considered to be endogenous to stand management, he also observes a clear effect of risk on the thinning regime was observed, with earlier and more intensive thinning as fire risk rises. This shows that the endogeneity of fire risk is a decisive factor in forest management and should therefore not be neglected in optimal rotation analyses.

This study builds on earlier work by Huang and Jana Szolgayova (2007), conducted at IIASA. The framework is extended to include stochastic biomass prices and models fire risk differently. This makes the model suitable to investigate the benefits of Earth observation in a novel way, while at the same time making a contribution to the existing literature on real options modeling of forest management.

1.2 References to Related Work

Optimal forest management modeling has a long history in forestry economics, going back as far as the mid-19th century, where Faustman's (1854) seminal work set off an ongoing debate about the right approach for determining optimal rotations in forests. An excellent overview of the related literature can be found in Chladna (2007). In this section we rather want to focus on the application of real options to forestry management and on the literature concerned with fire risk in particular.

Morck et al. (1989) was probably the first paper introducing real options to forestry economics. While Morck et al. (1989) used the contingent claim approach to value forestry lease under uncertainty about timber prices and timber inventories, later work by Thomson (1992) modeled these decisions in a discrete framework and used the lattice method. Most of the more recent real options literature in forestry management decision-making focuses on stochastic biomass prices and forest growth or combinations of the same (e.g. Insley, 2002; or Saphores, 2003). Alvarez and Koskela (2004) have further investigated the impact of stochastic interest rates. A more elaborate review of these

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studies can be found in Chladna (2007). Her work differs from the other studies insofar as she considers the optimal rotation period under the assumption of stochastic wood and stochastic carbon prices, regarding the forest as a potential carbon sink giving it some value beyond the supply of biomass.

With respect to fire risk and its impact on forestry management, there are several studies computing the rotation age maximizing the profits from selling timber. Seminal work includes Martell (1980), Routledge (1980) and Reed (1984). While Martell (1980) and Routledge (1980) use discrete time and fire probabilities, which are dependent on stand age, Reed (1984) considers optimal rotation in a continuous time framework, where fire risk is independent of stand age. Later work also included other aspects to the analysis. Caulfield (1988), for example, incorporated risk aversion.

As regards the methodologies employed in these frameworks, a diversity of approaches can be observed: Cohan et al. (1986) use decision trees to analyze different sources of uncertainty, including fire, to find optimal decisions concerning fuel and timber management. Reed and Errico (1986), make use of Monte Carlo simulations to determine the optimal harvesting schedule. Gassmann (1989) optimizes the expected harvested timber volume of timber over a finite planning horizon, where random parts of the forest can be lost due to fires. Boychuk and Martell (1996) employ multistage stochastic programming methods to optimize forest management given that timber supply should be maintained in the long run.[1] A more comprehensive overview can be found in González Olabarria (2006).

The work presented in this paper will differ from the reviewed literature in various points: it will include both a stochastic timber price and stochastic incidence of fire dependent on stand age; it will explicitly employ a real options approach and the associated valuations and interpretations thereof; and the model will be formulated so as to enable an analysis of decreased fire hazard due to Earth observation and the impact of this on income and forestry management behavior.

1.3 Overview

The rest of the paper will be organized as follows: section 2 will present the modeling framework very briefly and also present the data that will be used in the analysis. Section 3 will explain the results, while the final section draws the corresponding conclusions.

2. MODELING FRAMEWORK

2.1 Forest management data

Similar to Huang (2007), we use the Forest Inventory and Analysis (FIA) database, documentation on which can be found at (http://www.ncrs2.fs.fed.us/4801/FIADB/fiadb_documentation/SNAPSHOT_DB_V2pt1_JULY_2006.pdf). FIA data are collected on a periodic basis. The database has a uniform data structure for forestry inventories. It contains extensive data on stand age, stand size, diameter, stocking status, height, species and other attributes. Table A shows the data extracted from the FIA database for one the 12 southern states of US. Using a statistical software package, plot level data were used to generate descriptive statistics for loblolly pine.

Table A. Descriptive statistics for loblolly pine

Variables	**unit**	**mean**	**std. dev.**
Growing stock volume	cubic feet/acre	1333.5	1110.89
Stand age	Years	18	7.771
Stand density	100 trees/ acre	3.92	3.396
Site productivity class	-	3.8	0.992

For the estimation of the forest's growth, we use the basic Richard's function: $GSV_i = a \cdot e^{b \cdot \ln^2 \frac{x_i}{c}}$, where the average growing stock volume (GSV) per tree on plot i depends on the stand age on plot i and a is the maximum value of GSV per tree, which is about 143 cubic feet in our case. Parameter b refers to the shape and c is the maximum age. Plotting the average GSV per tree against stand age shows that this function is S-shaped.

Furthermore, a single tree on a forest stand will obviously grow faster because of the ample supply of water, light and nutrients. In fact, the volume of a tree in a full-stocked stand will only be 25% of that of a single tree. We use Huang's (2007) self-thinning line in order to adjust the GSV function for this factor. We also use the same method as Huang (2007) to extend the one-tree model to a one-acre model and estimate the diameter as a function of GSV per tree, which is an increasing relationship (but at a diminishing rate) given the data.

2.1 Real Options Model

Given the growth model referred to in the last section, we can now turn to the real options model to determine the optimal forest management schedules in the face of fire risk. X defines the current status of the forest stand. It is thus a vector including stand age and thinning status, where the latter is described by thinning frequency and the year/years of thinning. Knowing X_t therefore implies knowing the site-specific stand GSV and the average diameter at time t. We consider this to be a Markov process, which means that the information for determining the probability distribution of future values of X is summarized in the current state X_t and is independent of past states.

The wood price is modeled as a stochastic, mean-reverting process, where the stumpage price data are assembled from Timber Mart-South (TM-S). The data is for three product classes, which are specified as (1) pulpwood (PW) at a d.b.h. of 4 to 9 inches, (2), chip-n-saw (CNS) at a d.b.h of 9 through 11 inches, and (3) saw timber (ST) with a d.b.h greater than 11 inches. For products that are smaller than pulpwood the biomass value is considered. The price per tin in US$ is 6.42 for PW, 25.8 for CNS, 40.97 for ST and 1 for the biomass value. Using these data, the product price is modeled as a function of the diameter, where we will use both a step-function and a continuous function and compare the results.

Following Huang (2007), planting costs are linear in planting density. Per-acre costs of growing trees are based on current loblolly pine plantation practice. The cost on burned land is lower than that on unburned land because less soil preparation is required.

Forest fires occur according to a Poisson process with arrival rate λ. The probability that a fire occurs is ($1-e^{-\lambda}$). λ is modeled as a function of stand age and stand density. λ is assumed to be

[1] Multi-stage optimisation problems can be formulated in such a way as to answer the same questions as real options models. However, they have the tendency to become computationally intensive when there are many periods and scenarios, since it requires decision-making at each stage depending on the prior history of states. Cheng et al (2004) compare the two approaches and their advantages and disadvantages in more detail.

decreasing with stand age, since older trees will be more resistant to fire. As fires are more probable on a denser forest stand, λ is increasing with stand density. Thinning thus helps to reduce fire risk in addition to fostering forest growth.

There are three managerial actions the forest manager can perform in each time period: (1) thin, (2) harvest and (3) do nothing. The action performed and the resulting state of the forest stand will then determine the immediate profits, i.e. the difference between the income from selling the harvested wood and the costs of doing so.

The associated optimal control problem can be solved recursively by fixing the terminal value to zero and choosing the optimal action, a_t[2], to maximize the following value function for all possible future states (depending also on fire occurrence) and wood price instances:

$$V(X_t, P_t) = \max_{a \in A(x_t)} \{\pi(X_t, a(X_t, P_t), P_t) +$$

$$+ e^{-r} E[V(X_{t+1}, P_{t+1}) | X_t, P_t]\}$$

This so-called Bellman function is composed of the immediate profits denoted by $\pi(\bullet)$ that are received upon harvesting and the continuation value (second part of the sum), which is the expected value of the value function in all possible future states and for all possible future prices given today's prices and state. The second part is thus the value from waiting and we compute it by using Monte Carlo simulation. This method was chosen, since it remains computationally efficient for a high degree of complexity and is rather precise when the discretization of the price is sufficiently fine. The output of the process is a table with the optimal action for each time period t, for each possible state X and for each possible wood price, P. To obtain the final outcome, we conduct 10,000 simulations and extract the corresponding decisions from the output table.

3. RESULTS: OPTIMAL ROTATIONS & LOSSES DUE TO LACK OF EARTH OBSERVATIONS

3.1 Optimal rotations & the impact of different product price functions

The optimal rotations have been computed with the above model for both a step-wise price function and a continuous price function. Figures 1 and 2 show the optimal forest management decisions for these continuous and step-wise price functions respectively.

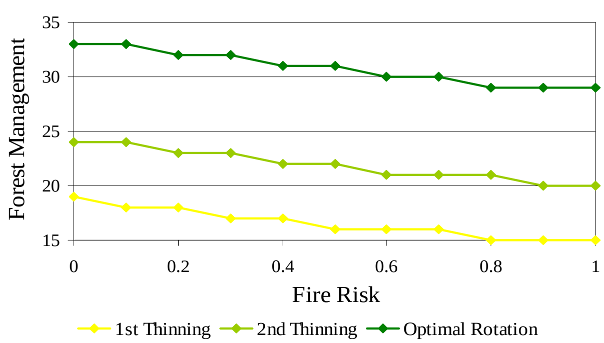

Figure 1. Fire risk impact on decisions with continuous prices.

[2] The actions are element of the set of feasible actions, A_t, where e.g. thinning is not a feasible action in the year following a harvest, i.e. it is not element of A_t in that time period.

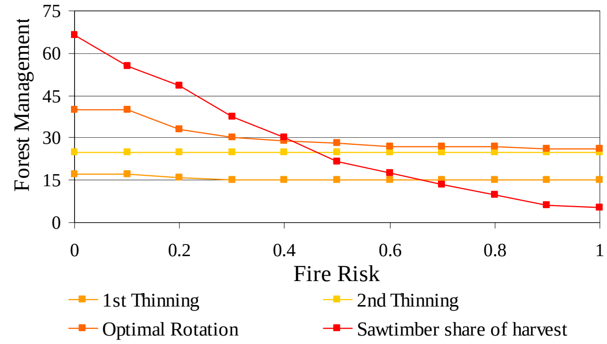

Figure 2. Fire risk impact on decisions with step-wise prices.

What can clearly be seen from both Figures is that higher fire risk (i.e. a larger probability that a fire will destroy the stand) leads to earlier harvesting, i.e. shorter rotations, and also to earlier thinning. In the continuous case, these relationships are smoother than in the step-wise case, since the harvesting time drops more drastically, once a threshold is surpassed, and stays constant until the next "step" of the price is reached. Note also that the continuous case starts out with an optimal harvesting time of 33, which falls to 29, as the fire risk increases, while the step-wise case starts out at 40, dropping to 26 with higher risk. The magnitude of the impact is thus also larger when stepwise prices are used.

Reducing fire risk by obtaining better information through EO will therefore lead to longer rotations and thus also higher-quality wood output: in Figure 2, the share of saw timber *rises* with *falling* fire risk. Since saw timber commands a higher price than chip-n-saw wood, this could lead to higher expected profits. The following section will therefore be devoted to analyzing the impact of fire risk on expected profits and the associated distributions.

3.2 Value of information & analysis of distributions

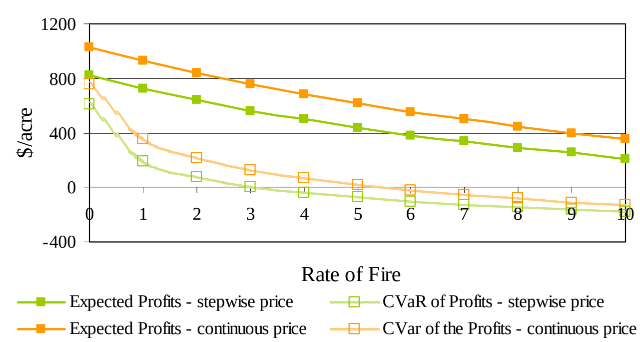

Figure 3. Impact of fire rate on profits in $/acre.

Figure 3 shows that expected profits fall, as the rate of fire increases, which is in line with our considerations from the previous section. In addition, risk measured by the Conditional Value-at-Risk (CVaR) also increases because the expected profit per acre that can be secured at 95% probability decreases as fire risk rises. For high rates of fire risk, expected profits might be negative even, since you would harvest so early that the costs exceed the income from selling chip-n-saw wood.

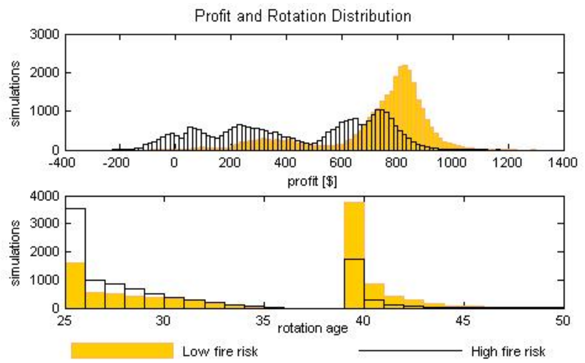

Figure 4. Profit distributions with different degrees of fire risk.

These insights are confirmed in Figure 4, where the distribution of expected profits for low fire risk (yellow) is much narrower than the one for larger fire risk (upper panel). Furthermore, the lower panel indicates that the average harvesting time increases substantially, as fire risk decreases. Together with the fact observed in the previous section – that the share of saw timber increases with falling risk – this observation explains the gains in expected profits that can be seen in the upper panel of the same panel and in Figure 3.

4. CONCLUSION

This paper has presented the results of a study on optimal rotations in a real options framework, where the major source of uncertainty is fire risk. The fire risk being defined as loss of a forest stand in case of fire, the results have shown that Earth observation can help to reduce fire risk and therefore lead to considerable gains in terms of expected profits and risk (and also actually in terms of CO_2 emissions, even though this has not been explicitly calculated). Rotations will be longer as a result of more security and the share of saw timber can be increased substantially.

REFERENCES

Alvarez, L.H.R., Koskela, E., “Optimal Harvesting Under Resource Stock and Price Uncertainty,” Discussion Paper, vol. 31. Helsinki Center of Economic Research, 2004. [Available at: http://ethesis.helsinki.fi/julkaisut/eri/hecer/disc/31]

Boychuk, D., Martell, D.L., “A multistage stochastic programming model for sustainable forest-level timber supply under risk of fire.” Forest Science 42:10-26, 1996.

Caulfield, J.P., “A Stochastic Efficiency Approach for Determining the Economic Rotation of a Forest Stand.” Forest Science 34:441-457, 1988.

Cohan, D., Haas, S.M. Radloff, D.L. and Yancik, R.F., “Using Fire in Forest Management: Decision Making Under Uncertainty.” Interfaces. 14:8-19, 1984.

Cheng L, Subrahmanian E, Westerberg A., “A comparison of optimal control and stochastic programming from a formulation and computation perspective,” Computers and Chemical Engineering, vol. 29:149-164, 2004.

Chladna, Z., “Determination of optimal rotation period under stochastic wood and carbon prices.” Forest Policy and Economics 9:1031-1045, 2007.

Dixit A, Pindyck R., “Investment under Uncertainty,” Princeton University Press: Princeton, 1994.

Faustmann, M., “Calculation of the value which forest land and immature stands possess for forestry.” Journal of Forest Economics 1:7-44, 1849.

Gassman, H.I., “Optimal harvest of a forest in the presence of uncertainty.” Canadian Journal of Forest Research 19:1267-1274, 1989.

González Olabarria, J.R., “Integrating fire risk into forest planning,” The Finnish Society of Forest Science, Faculty of Forestry, Dissertationes Forestales, no 23, 2006.

Huang, J., “Impact of Fire Risk on Forest Manager’s Behavior and Welfare — Real Options Approach,” YSSP report, IIASA: Laxenburg, 2007.

Insley, M., “A real options approach to the valuation of a forestry investment.” Journal of Environmental Economics and Management 44:471-492, 2002.

Khabarov, N., Moltchanova, E. and Obersteiner, M., “Valueing Weather Observation Systems for Forest Fire Management.” IEEE Systems Journal, vol. 2:349-357, 2008.

Martell, D.L., “The optimal rotation of a flammable forest stand.” Canadian Journal of Forest Research 10:30-34, 1980.

Morck, R., Schwartz, E., Stangeland, D., “The valuation of forestry resources under stochastic prices and inventories.” The Journal of Financial and Quantitative Analysis 24:473-487, 1989.

Reed, W.J., “The effects of the risk of fire on the optimal rotation of a forest.” Journal of Environmental Management 11:180-190, 1984.

Reed, W.J. and Errico, D., “Optimal harvest scheduling at the forest level in the presence of the risk of fire.” Canadian Journal of Forest Research 16:266 – 278, 1986.

Routledge, R.D., “The effect of potential catastrophic mortality and other unpredictable events on optimal forest rotation policy.” Forest Science 26:389-399, 1980.

Saphores, J.D., “Harvesting a renewable resource under uncertainty.” Journal of Economic Dynamics and Control 28:509-529, 2003.

Thomson, T.A., “Optimal forest rotation when stumpage prices follow a diffusion process.” Land Economics 68:329-342, 1992.

On Optimal Placement of Tsunami Detectors and Importance of Detector's Network Density for Tsunami Early Warning Systems

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Abstract

We consider a model of a tsunami early warning system (TEWS) and one of its main elements — a sensor network measuring offshore sea level in real time to detect tsunami waves and issue a warning reasonable time ahead of the wave arrival at a coastline. Our main focus is the optimal placement of tsunami detectors and dependence of a warning lead time on the density of the detector's network, which has not been studied before. We explore two simple configurations of a TEWS model consisting of one settlement located onshore of a constant-depth basin and two types of tsunamigenic zones: one represented by a straight infinite line (or its finite segment) and the other having the form of a half-round. We develop an optimal sensor placement method for both cases and derive asymptotic assessments of the number of detectors depending on lead warning time, highlighting the issue of TEWS cost-benefit efficiency for areas where tsunamigenic zone location is near to a populated coastline. We also show that for the purposes of network density analysis an aggregated scalar parameter representing the relative reduction of lead warning time over the wave arrival time can be efficiently used. We conclude with discussion of implications these results have for real applications.

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1 Introduction

Tsunamis as a natural disaster phenomena greatly vary in size. More often relatively small events occur affecting small part of a coastline and that impact can be accounted for in terms of tenths of lost lives. Larger events occur from time to time killing hundreds and even thousands of people. A recent Indonesia 2006 event demonstrated a catastrophic scale of a tsunami event producing hundreds of thousands of loss in terms of lost lives. This makes the problem of protecting against a tsunami very serious and of high priority.

Because of the nature of tsunami, prevention is not possible at all, and protection against this type of disaster is quite limited and extremely expensive. For instance, building solid walls along threatened coastlines does not provide a 100% protection, since if a tsunami wave has a height exceeding those of the wall, the protection is useless. Building protection walls of extreme height leads to extreme costs and hence does not appear to be reasonable in economic terms. Under these conditions a timely evacuation of people endangered by a tsunami becomes an viable and important strategy of tsunami hazard confrontation.

In order to provide a timely evacuation, among all other measures (preparedness of transportation, awareness of people, properly functioning warning dissemination channels, etc.) a timely early warning should be issued at the first place. Currently operating tsunami early warning systems (TEWS) include various types of sensors e.g. seismographs to assess the seismic impact of an earthquake on water mass, GPS receivers to measure crust deformation at the seafloor level and water gauges and bottom pressure recorders (BPR). Those two later types of measuring equipment are able to provide real-time direct measurements of sea level, thus providing a more reliable result than the former types of devices providing only indirect information related to tsunamis. Without using of BPRs, a TEWS usually generates a high proportion of false alarms which are costly in terms of expenses associated with evacuation and also affecting the thrust of people to the TEWS [make ref()]. So, BPRs being an integral part of a modern TEWS play an important practical role of minimizing false alarms and to a large degree the decision making rules implemented in TEWSs are based on the information provided by BPRs in real time. As an example of BPR there is an implementation called DART (Deep ocean array? of recorder and transmitters) implemented by NOA/PMEL office. In the present paper we will deal exactly with the BPR type of tsunami sensors and further will refer to them simply as *sensors*.

2 Optimal Sensor Placement Problem

The problem of optimal sensor placement for tsunami detection is considered in a few papers [make ref()]. The subject of our research here is not only the optimal placement of sensors under different constraints (e.g. limited number of sensors or provision of a fixed warning lead time), we rather are interested on how sensitive is the TEWS to the density of its sensor network. This question is of principal importance because improving the level of safety for tsunami endangered coastal communities means (among other) increasing lead warning time, which in turn means increase of number of optimally placed sensors. In order to investigate on the warning time – number of sensors relation we formulate the following abstract (simplified) problem.

Let consider an infinite water basin of a constant depth, a tsunamigenic zone (TZ), and a point representing a settlement to be warned in advance of time t_w about tsunamis originating from any point located in the TZ. We further consider two types of TZs: straight infinite line (further referred to as *A-problem*) and a half-circle of a certain radius with its center located in the settlement (*B-problem*). We do not constrain the tsunami generation mechanism, so it can be caused both by an underwater earthquake or underwater landslide.

The problem is to find the locations of sensors such that the total number of sensors is minimal and the settlement is warned time t_w in advance of arrival of tsunami.

To develop a formal definition of that optimization problem let denote TZ as $\mathcal{Z} \subset \mathbb{R}^2$ – it's a set of points that can be a source of tsunami. Let denote $t(\cdot,\cdot) : \mathbb{R}^2 \times \mathbb{R}^2 \to \mathbb{R}$ a function of wave arrival time, such that $t(a, b)$ is the time which takes a wave originated at point a to reach the point b. Let further denote point c the location of a city (or settlement), and $\{d_i\}$, $i = 1, \dots, n$ the points where detectors are located. Under this notation, the formal definition of the problem is as follows.

$$\begin{aligned} &\min n \quad \text{s.t.} \\ &\forall\, z \in \mathcal{Z} \quad \exists\, i \in \{1, \dots, n\} \quad \text{such that} \\ &t(z, c) - t(z, d_i) \geq t_w. \end{aligned} \tag{1}$$

The detector locations $\{d_i\}$ are subject to choice delivering the optimal value in the problem (1). In A-problem $\mathcal{Z} = \{z : (z, a) = b\}$ for some fixed vector $a \in \mathbb{R}^2$ and constant b (a straight line); in B-problem $\mathcal{Z} = \{z : |z - c| = r,\ (z - c, a) \geq 0\}$ for some fixed radius r and orientation vector $a \in \mathbb{R}^2$ (half-circle).

3 Optimal Solution

A-problem. Let introduce an euclidean coordinate system such that OY axis coincides the straight line shaped tsunamigenic zone and a settlement is located at point $(x_0, 0)$. Let us denote v the constant wave spread velocity, d_i the location of the i^{th} sensor on the OY axis, and constant $\hat{r} = vt_w$, then the optimal solution is defined by the following recurrent formulas:

$$\begin{aligned} d_1 &= -\hat{r}, \\ r_k &= \frac{x_0^2 + d_k^2 - \hat{r}^2}{2(\hat{r} - d_k)}, \\ d_{k+1} &= d_k + 2r_k, \\ k &= 1, 2, \ldots . \end{aligned} \tag{2}$$

The stopping rule limiting the number of sensors to be installed is $k \leq k^*$ such that $d_{k^*} \geq \hat{r}$.

B-problem. Let us consider a half circle-shaped TZ of radius R with a settlement in the circle's center. The minimal number of sensors N needed to issue a timely warning is defined by the following formula

$$N = \left\lceil \frac{\pi}{2 \arcsin(r/R)} \right\rceil, \quad \text{where} \quad r = R - \hat{r}. \tag{3}$$

Where $\lceil a \rceil$ denotes a minimal integer number such that it is greater or equal to a.

Figures () and () show the interpolation of the derived relations (2) and (3) by a hyperbolic function

$$y = \frac{a}{\alpha - 1} + b$$

for some constants a and b calculated based on the constraint of having left and right point of the graphs equal. One may see a good agreement for the values of α close to 1 from the left.

4 Numerical Examples

As an illustration of the derived relation ref() we have calculated several examples of what number of sensors could be needed for different depths, distances to tsunamigenic zones, and required warning lead times, see Table 1.

NoSC	NoSL	WTT alpha	300	240	180	120	60	30	20
1	1	0	0	0	0	0	0	0	0
2	2	0.1	30	24	18	12	6	3	2
2	2	0.2	60	48	36	24	12	6	4
3	2	0.3	90	72	54	36	18	9	6
3	2	0.4	120	96	72	48	24	12	8
3	2	0.5	150	120	90	60	30	15	10
4	3	0.6	180	144	108	72	36	18	12
6	3	0.7	210	168	126	84	42	21	14
8	4	0.8	240	192	144	96	48	24	16
16	6	0.9	270	216	162	108	54	27	18
32	9	0.95	285	228	171	114	57	29	19
79	15	0.98	294	235	176	118	59	29	20

Table 1: Lead warning time (in minutes) depending on wave travel time (WTT) and installed number of sensors in case of half-circular (NoSC) and straight line shaped (NoSL) tsunamigenic zones.

One can see from the table that the distance to TZ in terms of wave travel time from source to the protected settlement is a crucial factor in efficiency of a TEWS. For instance, in A-problem if a settlement is 3 hours (180 minutes) away of TZ, only 3 sensors are required to provide a 108 minutes lead warning time; if a settlement is 2 hours (120 minutes) away of TZ the necessary number of sensors is doubled and 6 sensors are needed to provide the same 108 minutes lead warning time. In B-problem, if a settlement is 5 hours (300 minutes) away of TZ, only 3 sensors are required to provide a 2.5 hour (150 minutes) lead warning time. For settlements located 4 hours (240 minutes) and 3 hours (180 minutes) away of TZ, the number of required sensors to provide the same 150 minutes warning time is two times more (6 sensors) and more than five times more (16 sensors) respectively. We used a bit greater warning times from the table (168 and 162 minutes respectively) which are the lowest values not lower than 150 in the corresponding columns of the table. This rough assessment based on pre-tabulated values is refined on figures () and (), where we have recalculated the required number of sensors (RNS) for several fixed values of lead warning time (LWT) and visualized the results depending on wave travel time (WTT) from the source to the settlement (which is equivalent of distance under our current assumptions). For instance, in A-problem for a warning time equal to 2 hours 40 minutes, the RNS doubles from 3 to 6 when the WTT reduces from 5 hours to 3 hours. At the same time RNS seems to be quite insensitive for LWT equal to both values of 40 and 50 minutes when WTT changes from 3 hours to 1.5 and 2 hours respectively, since RNS remains constant equal to 2. In B-problem one may see the same effects of rapid increase of RNS for LWT = 2 h 40 min and WTT$\in [3, 5]$ (increase from 4 to 16 sensors) as well as insensitivity of RNS for LWT = 55 min and WTT$\in [2, 3]$ (constant 3 sensors).

The conclusion from these numerical experiments is that quite many sensors may be needed to protect settlements located close to a tsunamigenic zone even though the resulting LWT may turn out to be relatively short. The marginal improvement of a LWT for settlements located near a TZ may be prohibitive expensive because of both the costs associated with the sensors setup and maintenance, as well as because of the thievery problem actual for some regions.

5 Real Bathymetry Application

In order to compare the rather theoretical results derived from (2) and (3) we demonstrate here the results of calculation of the number of sensors for Okhotsk Sea bathymetry using the ANI model developed and supported by Sakhalin Branch of Russian Geographic Society.

6 Discussion and Concluding Remarks

Of course, the model presented here is simplified in many aspects.

If a tsunamigenic zone can be represented as a combination of a half-circle and straight line, the needed number of sensors lies between the two assessments (corresponding to half-circle and straight line). If TZ lies beyond a straight line the number of sensors calculated by the model is an upper assessment.

This rather theoretical model is not directly applicable to real conditions because of the following considerations.

The acting space is an Earth spheroid and not a plane. Furthermore, there is not a uniform water surface, yet coasts which can reflect waves and also protect a settlement from an approaching tsunami. In our model we did not include a spheroid in order to avoid unnecessary mathematical complexity assuming that the spheroid's radius is big enough in order the plane approximation to be valid. To make sure that the errors arising from the spheroid approximation by a plane are admissible, we calculated for three points A(150W,0), B(130W,0), and C(130W,20N) the distance AC. The distances AB and BC are about 2200 km which is about 3 hours wave travel time for a 4000 m depth. The plane approximation of this disposition delivers a very small difference (about 1%) of the exact distance which is about 3100 km. So, this sample calculation shows that the distance values do not differ too much when calculating for spheroid or approximated by a plane.

Anyway, the model is designed in such a way (representation of a TZ by an abstract infinite line) that it is implicitly assumed that the distance from a settlement to a TZ is smaller than the length of the TZ. That means that the approximation is valid for the settlements located quite close to a TZ (i.e. a distance of a few thousands of kilometers as demonstrated in the sample calculation above is okay).

Tsunamigenic zones boundaries are not strictly defined.

If a shape of a tsunamigenic zone does not fit circle–straight line boundary, and cannot be reasonably approximated by their combination, the method is not applicable.

Constant depth assumption is unrealistic and bathymetry is important for real applications, since it has to do not only with wave travel times but also with travel amplitudes and hence reliability of detection.

A real sensor placement problem includes additional constraints such as definite distance from the TZ so that the sensors do not get damaged by an underground earthquake and perhaps also consecutive underwater landslide.

Also bottom conditions i.e. how hard it is to setup a sensor in a particular location and service it.

Nevertheless, the main goal of this research was not to provide a methodology applicable for designing operational TEWSs, but rather to study on the properties of the network density for TEWS performance assuming the network is optimal in terms of the number of sensors comprising it. The main conclusion is that for a close TZ even a dense (and expensive) sensor network may provide bad warning lead time, whereas for distant TZ only a few sensors provide admissible TEWS performance. It means that in real case studies the activities on TEWS should be split between actual deployment of a sensor network and increasing awareness and preparedness of local coastal communities to make even short warning times useful for saving lives.

7 Acknowledgments

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8 Appendix: Proof of Optimality

Let us introduce the following notation. For two points A and B on a plane, AB denotes a segment with its ends at A and B, and $|AB|$ denotes the length of AB. $\mathcal{S}(A, r)$ denotes a circle of a radius r and its center in the point A, i.e. $\mathcal{S}(A, r) = \{B : |AB| = r\}$; $\mathcal{B}(A, r)$ denotes a round of a radius r and its center in the point A, i.e. $\mathcal{B}(A, r) = \{B : |AB| \leq r\}$. We will say that two circles $\mathcal{S}(O_1, r_1)$ and $\mathcal{S}(O_2, r_2)$ are *osculating* if their intersection is just one point $\mathcal{S}(O_1, r_1) \cap \mathcal{S}(O_2, r_2) = \{C\}$. We will say that two osculating circles $\mathcal{S}(O_1, r_1)$ and $\mathcal{S}(O_2, r_2)$ are *osculating from inside* if $\mathcal{B}(O_1, r_1) \subset \mathcal{B}(O_2, r_2)$ or $\mathcal{B}(O_2, r_2) \subset \mathcal{B}(O_1, r_1)$ and we will say that the circles are *osculating from outside* if the intersection of the two respective rounds is just one point $\mathcal{B}(O_1, r_1) \cap \mathcal{B}(O_2, r_2) = \{C\}$. According to that definition, if a radius of one of the two osculating circles is zero, then the circles are osculating both from inside and outside. Let us denote also the *interior* of a round as

$$\operatorname{int} \mathcal{B}(A, r) = \{B : |AB| < r\}.$$

Lemma 1. *Let us consider two circles $\mathcal{S}(O_1, r_1)$ and $\mathcal{S}(O_2, r_2)$ osculating from outside. Then for any point $D \in \mathcal{S}(O_2, r_2)$ and any point $A \in O_2D$ the following relation is always true:*

$$|AO_1| - r_1 \geq |AD|. \tag{4}$$

Proof. If $r_2 = 0$ then (4) derives to $r_1 - r_1 \geq 0$, which is apparently true. Now we assume that $r_2 > 0$. If $A = O_2$ then (4) derives to $|O_2O_1| - r_1 = r_2 \geq r_2 = |AD|$ (true). If $A = D$ then (4) derives to $|AO_1| - r_1 = |O_1D| - r_1 \geq |DD| = 0$ (true, because $D \notin \operatorname{int} \mathcal{B}(O_1, r_1)$). Now let us consider the case $A \neq O_2$ and $A \neq D$. Let us denote $C_1 = AO_1 \cap \mathcal{S}(O_1, r_1)$, $C_2 = AO_1 \cap \mathcal{S}(O_2, r_2)$, $F = AO_1 \cap \mathcal{S}(A, |AD|)$. Since $F \in \mathcal{B}(A, |AD|) \subset \mathcal{B}(O_2, r_2)$ then

$$|AF| \leq |AC_2| \leq |AC_1| \tag{5}$$

(otherwise if $|AC_2| > |AC_1|$ it would mean that $C_2 \in \operatorname{int} \mathcal{B}(O_1, r_1)$ and $C_2 \in \mathcal{B}(O_2, r_2)$ at the same time which is impossible). From (5) it follows that $|AF| \leq |AC_1|$ which is equivalent to $|AD| \leq |AC_1|$ which is equivalent to $|AD| \leq |AO_1| - r_1$. $\square$

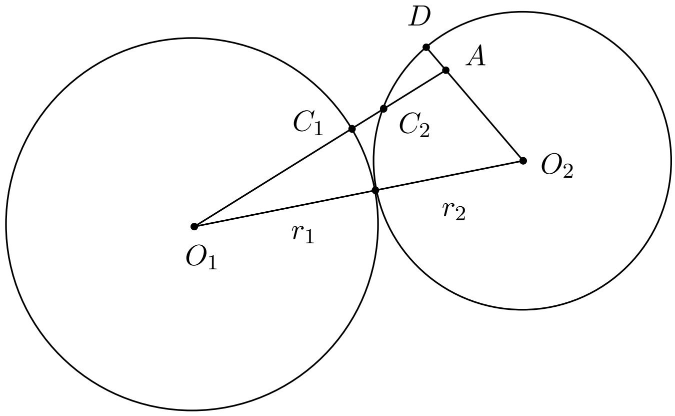

Figure 1: Two circles osculating from outside.

Remark 1. Lemma 1 is true also in case if two rounds do not intersect: $\mathcal{B}(O_1, r_1) \cap \mathcal{B}(O_2, r_2) = \varnothing$. This statement immediately follows from the consideration of a circle $\mathcal{S}(O_1, r_1')$, $r_1' > r_1$, such that $\mathcal{S}(O_1, r_1')$ and $\mathcal{S}(O_2, r_2)$ are osculating from outside and the inequality

$$|AO_1| - r_1 > |AO_1| - r_1' \geq |AD|,$$

which implies (4).

We will say that there exists a solution of a tsunami sensors placement problem for a given settlement, tsunamigenic zone $\mathcal{Z}$, and required lead warning time t_w, if there exists a sensor network providing the lead warning time t_w or better for any wave generated by any point of $\mathcal{Z}$. Further, we will say that a *placement of tsunami sensors is optimal* if there is no solution of the problem having smaller number of sensors.

8.1 A-problem

Theorem 1 (Finite segment in A-problem)**.** *Let a Cartesian coordinate system is defined on a plane, a settlement is located at the point $X(x,\ 0)$ and the tsunamigenic zone is represented by a segment $\mathcal{Z} = \tilde{Y}\hat{Y}$, on the Y-axis, where $\tilde{Y}(0, -a)$ and $\hat{Y}(0, a)$. Let the constant wave spread velocity is v and the required lead warning time is t_w such that $x > vt_w$. Then the solution of the tsunami sensors placement problem exists, and the following* *placement of k^* tsunami detectors $D_k(0, d_k)$ is optimal:*

$$
\begin{aligned}
d_1 &= -a + r_0, \quad r_0 = \sqrt{x^2 + a^2} - \hat{r}, \quad \hat{r} = vt_w, && (6)\\
d_{k+1} &= d_k + 2r_k, && (7)\\
r_k &= \frac{x^2 + d_k^2 - \hat{r}^2}{2(\hat{r} - d_k)}, && (8)\\
k &= 1, 2, \ldots, k^* - 1, &&\\
k^* &: d_{k^*} \geq a - r_0, && (9)\\
& \quad d_k < a - r_0 \quad \forall\, k < k^*. && (10)
\end{aligned}
$$

Proof. First, we will narrow down the possible optimal configurations of sensors to be considered based on the observation that any configuration of detectors in $\mathbb{R}^2$ can be transformed to a configuration where all detectors are located on the Y-axis by projecting each detector's location onto the segment $\mathcal{Z}$. This transformation does not increase the lead warning time because moving a detector from its original location to a projected location does not increase the distance to any point on the segment $\mathcal{Z}$, hence does not increase the detection time for a wave originating form any point on the segment $\mathcal{Z}$. It means that if some configuration of sensors is optimal, the projected configuration will also be optimal and because now we are not interested in the entire set of possible optimal solutions we may restrict them to those having sensors placed on $\mathcal{Z}$.

Let us show that $k^* < +\infty$. Since under the conditions of the theorem $x > \hat{r}$, the following inequality holds

$$x^2 + d_k^2 - \hat{r}^2 \geq x^2 - \hat{r}^2 > 0 \quad \forall\, k < k^*. \tag{11}$$

From (6) and (10) it follows that

$$\hat{r} - d_k > \hat{r} - a + r_0 = \hat{r} - a + \sqrt{x^2 + a^2} - \hat{r} > 0 \quad \forall\, k < k^*. \tag{12}$$

From (8), (11), and (12) it follows that

$$r_k > 0 \quad \forall\, k < k^*. \tag{13}$$

And this leads to the fact that $\{d_k\} \nearrow$, i.e.

$$d_{k+1} > d_k \quad \forall\, k < k^*. \tag{14}$$

Based on this, we have $\{\hat{r} - d_k\} \searrow$ and

$$\max_{k<k^*}(\hat{r} - d_k) = \hat{r} - d_1.$$

Taking this into account, the following chain of inequalities is true

$$r_k = \frac{x^2 + d_k^2 - \hat{r}^2}{2(\hat{r} - d_k)} \geq \frac{x^2 - \hat{r}^2}{2 \max\limits_{k<k^*}(\hat{r} - d_k)} \geq \frac{x^2 - \hat{r}^2}{\hat{r} - d_1} \equiv \hat{\varepsilon} > 0. \tag{15}$$

From (15) and (7) it follows that

$$\begin{aligned} d_{k+1} = d_k + 2r_k \Rightarrow d_{k+1} \geq d_k + 2\hat{\varepsilon} \Rightarrow d_{k+1} \geq d_1 + 2k\hat{\varepsilon} \Rightarrow \\ d_k \geq d_1 + 2(k-1)\hat{\varepsilon}. \end{aligned} \tag{16}$$

Let us consider inequality

$$\begin{aligned} d_1 + 2(k-1)\hat{\varepsilon} \geq a - r_0 \quad \Leftrightarrow \\ k - 1 \geq \frac{a - r_0 - d_1}{2\hat{\varepsilon}} = \frac{a - r_0 + a - r_0}{2\hat{\varepsilon}} = \frac{a - r_0}{\hat{\varepsilon}}. \end{aligned} \tag{17}$$

From (16) and (17) it follows that $d_k \geq a - r_0$ for sure if

$$k \geq \frac{a - r_0}{\hat{\varepsilon}} + 1,$$

which automatically means that the stopping condition (9) is met at least for such k and hence

$$k^* \leq \frac{a - r_0}{\hat{\varepsilon}} + 1, \tag{18}$$

that is k^* is limited from above, hence finite, and its definition in form of (9) and (10) is correct.

Let us denote t_{AB} the wave travel time from point A to point B. Then the timely warning condition for any tsunamignic point source Y, settlement point X and detector located at point D is

$$t_{YX} - t_{YD} \geq t_w \tag{19}$$

meaning that a wave originating from point Y will arrive at point X not earlier than t_w (minutes) after detection by a sensor located in point D. This inequality is apparently equivalent to

$$vt_{YX} - vt_{YD} \geq vt_w$$

that is equivalent to

$$|YX| - \hat{r} \geq |YD|. \tag{20}$$

The equation (20) is the reformulation of a timely warning condition (19) in terms of distance instead of time.

Let us introduce auxiliary points $Y_k(0, y_k)$ such that

$$y_1 = -a, \quad y_{k+1} = d_k + r_k, \quad k = 1, 2, \dots, k^* - 1. \tag{21}$$

Then since $y_{k+1} + r_k = d_k + 2r_k$ the following relation is true

$$d_{k+1} = y_{k+1} + r_k, \quad k = 1, 2, \dots, k^* - 1. \tag{22}$$

Let us denote $\mathcal{A}(Y) \subset \mathbb{R}^2$ the *safe detection area* of a tsunamigenic point Y, i.e. the set where a sensor should be placed to provide a timely warning to the settlement X for a wave originating from the point Y:

$$\mathcal{A}(Y) = \{D : \text{ condition (20) is met}\}.$$

We will say that detector D is *covering a tsunamigenic point* Y if $D \in \mathcal{A}(Y)$. We will say that detector $D(0, d)$ is covering tsunamigenic point $Y(0, y)$ *from above* [or *below*] and write $D \in \overline{\mathcal{A}}(Y)$ [or $D \in \underline{\mathcal{A}}(Y)$] if $D \in \mathcal{A}(Y)$ and $D_\varepsilon \notin \mathcal{A}(Y)$ for all $\varepsilon > 0$, where detector $D_\varepsilon(0, d + \varepsilon)$ [or $D_\varepsilon(0, d - \varepsilon)$].

Let us explain the meaning of the construction (6)–(10) and (21). First sensor D_1 is covering the tsunamigenic point $Y_1 = \tilde{Y}$ because

$$r_0 = |Y_1X| - \hat{r} \geq |Y_1D_1| = |y_1 - d_1| = |-a + a - r_0| = r_0.$$

So, the timely warning condition (20) is met and $D_1 \in \mathcal{A}(Y_1)$. Moreover, considering a detector $D_{1\varepsilon}(0, d_1 + \varepsilon)$ for all $\varepsilon > 0$, the following inequality holds:

$$|Y_1X| - \hat{r} = r_0 < r_0 + \varepsilon = |Y_1D_{1\varepsilon}|,$$

hence $D_{1\varepsilon} \notin \mathcal{A}(Y_1)$ and $D_1 \in \overline{\mathcal{A}}(Y_1)$, i.e. D_1 is covering Y_1 from above. At the same time, the sensor D_1 is covering Y_2, since, taking into account that $y_2 = d_1 + r_1$, $|Y_2X| = \sqrt{x^2 + y_2^2}$, $|Y_2D_1| = |d_1 - y_2| = r_1 > 0$, and (12) the following relations are equivalent:

$$\begin{gathered}
|Y_2X| - \hat{r} = |Y_2D_1| \quad \Leftrightarrow \quad \sqrt{x^2 + (d_1 + r_1)^2} = \hat{r} + r_1 \quad \Leftrightarrow \\
x^2 + d_1^2 + 2d_1r_1 + r_1^2 = \hat{r}^2 + 2r_1\hat{r} + r_1^2 \quad \Leftrightarrow \\
r_1 = \frac{x^2 + d_1^2 - \hat{r}^2}{2(\hat{r} - d_1)}.
\end{gathered}$$

The last equality is true, hence $D_1 \in \mathcal{A}(Y_2)$. Moreover, $D_1 \in \underline{\mathcal{A}}(Y_2)$, because for all $\varepsilon > 0$ $D_{1\varepsilon}(0, d_1 - \varepsilon) \notin \mathcal{A}(Y_2)$ since $|Y_2D_{1\varepsilon}| = r_1 + \varepsilon > r_1 = |Y_2D_1| = |Y_2X| - \hat{r}$.

To summarize, $D_1 \in \overline{\mathcal{A}}(Y_1)$ and $D_1 \in \underline{\mathcal{A}}(Y_2)$. It can be proved in the same way as for $k = 1$ that

$$\begin{aligned} &D_k \in \overline{\mathcal{A}}(Y_k), \quad k = 1, ..., k^*, \\ &D_k \in \underline{\mathcal{A}}(Y_{k+1}), \quad k = 1, ..., k^* - 1. \end{aligned} \tag{23}$$

From (6), (21), (22), and (15) it follows that the following chain of inequalities is true

$$y_1 < d_1 < y_2 < d_2 < \cdots < y_{k^*-1} < d_{k^*-1} < y_{k^*} < d_{k^*}. \tag{24}$$

Based on the obvious fact that $\overline{\mathcal{A}}(Y) \subset \mathcal{A}(Y)$ and $\underline{\mathcal{A}}(Y) \subset \mathcal{A}(Y)$ and with application of lemma 2, (23) implies

$$\begin{aligned} &D_k \in \mathcal{A}(Y) \quad \forall\, Y \in Y_k D_k, \quad k = 1, ..., k^*, && \text{(a)} \\ &D_k \in \mathcal{A}(Y) \quad \forall\, Y \in D_k Y_{k+1}, \quad k = 1, ..., k^* - 1, && \text{(b)} \end{aligned} \tag{25}$$

which together with (24) leads to

$$\forall\, Y \in Y_1 D_{k^*} \quad \exists\, D_k : \; D_k \in \mathcal{A}(Y), \quad k \in \{1, ..., k^*\}. \tag{26}$$

Let us show that

$$D_{k^*} \in \mathcal{A}(\hat{Y}). \tag{27}$$

Let us consider the case if $d_{k^*} \leq a + r_0$. Together with (9) this means that (27) is correct, since $\mathcal{A}(\hat{Y}) = \mathcal{B}(\hat{Y}, r_0)$ (see the definition of $\mathcal{A}(Y)$). Now let us consider the case if $d_{k^*} > a + r_0$. Then from (26) and $Y = \hat{Y}$ it follows that (27) is true since $D_k \notin \mathcal{A}(\hat{Y})\ \forall\, k < k^*$ (see (10)) and (27) is proved to be true.

Application of lemma 2 to (27) leads to

$$\forall\, Y \in D_{k^*}\hat{Y} \quad D_{k^*} \in \mathcal{A}(Y), \tag{28}$$

which together with (26) leads to

$$\forall\, Y \in \tilde{Y}\hat{Y} \quad \exists\, D_k : \; D_k \in \mathcal{A}(Y), \quad k \in \{1, ..., k^*\}. \tag{29}$$

This means that the sensor network $\{D_k\}_{k=1}^{k^*}$ is a solution (may be not optimal) of a tsunami sensors placement problem for a given settlement X, tsunamigenic zone $\mathcal{Z}$, and required lead warning time t_w.

Let us now prove the optimality of the detectors placement (6)–(10). Let us consider any other placement of detectors $\{\tilde{D}_k\}_{k=1}^{\tilde{k}}$ such that it covers $\mathcal{Z}$ i.e.

$$\forall\, Y \in \tilde{Y}\hat{Y} \quad \exists\, \tilde{D}_k : \; \tilde{D}_k \in \mathcal{A}(Y), \quad k \in \{1, ..., \tilde{k}\}. \tag{30}$$

According to the remark on projecting the sensor locations onto $\mathcal{Z}$ we made in the beginning of the proof, we may assume that $\tilde{D}_k$ have coordinates $(0, \tilde{d}_k)$. Let us introduce the following sets

$$\begin{aligned}
&\mathcal{M}_1 = (-\infty, d_1], \\
&\mathcal{M}_2 = (d_1, d_2], \\
&\quad \ldots, \\
&\mathcal{M}_{k^*} = (d_{k^*-1}, d_{k^*}].
\end{aligned}$$

Let us show that

$$\forall\, i \in \{1, \ldots, k^*\} \quad \exists\, j \in \{1, \ldots, \tilde{k}\} \,:\, \tilde{d}_j \in \mathcal{M}_i. \tag{31}$$

Let us first consider the case $i = 1$. If $\tilde{d}_j \notin \mathcal{M}_1 \;\forall\, j$ then $\tilde{d}_j > d_1 \;\forall\, j$ hence $\delta_j = \tilde{d}_j - d_1 > 0$ and

$$\tilde{D}_j = D(0, d_1 + \delta_j) \notin \mathcal{A}(Y_1) \quad \forall\, j, \tag{32}$$

because $D_1 \in \overline{\mathcal{A}}(Y_1)$ as it was shown in (23). From (32) it follows that point Y_1 is not covered, which contradicts the assumption (30) that $\{\tilde{D}_k\}_{k=1}^{\tilde{k}}$ is the solution of the sensor placement problem.

Let us consider now the case $i \,:\, 2 \leq i \leq k^*$ $(k^* \geq 2)$ and assume the contrary i.e.

$$d_j \notin \mathcal{M}_i \quad \forall\, j. \tag{33}$$

Let us introduce the sets

$$\begin{aligned}
&\mathcal{J}_- = \{j \,:\, \tilde{d}_j \leq d_i\}, \\
&\mathcal{J}_+ = \{j \,:\, \tilde{d}_j > d_i\}.
\end{aligned}$$

Assumption (33) implies that

$$\mathcal{J}_- \cup \mathcal{J}_+ = \{1, \ldots, \tilde{k}\}, \tag{34}$$

Let us define $\delta_j = \tilde{d}_j - d_i > 0$, $\forall\, j \in \mathcal{J}_+$. Since $D_i \in \overline{\mathcal{A}}(Y_i)$ (see (23)), then the application of lemma 3 leads to

$$\forall\, j \in \mathcal{J}_+ \quad \exists\, \bar{\varepsilon}_j > 0 : \quad \tilde{D}_j = D_{+\delta}(0, d_i + \delta_j) \notin \mathcal{A}(Y_{+\varepsilon}), \quad \forall\, \varepsilon :\, 0 < \varepsilon \leq \bar{\varepsilon}_j, \tag{35}$$

here $Y_{+\varepsilon}(0, y_i + \varepsilon)$. Let us define

$$\bar{\varepsilon} = \min_{j \in \mathcal{J}_+} \bar{\varepsilon}_j > 0.$$

Based on lemma 5 we can define

$$\tilde{\varepsilon} = \min(\bar{\varepsilon}, \frac{a - y_{k^*}}{2}) > 0,$$

then

$$Y_{+\tilde{\varepsilon}} \in \tilde{Y}\hat{Y} \tag{36}$$

and the following statement is true

$$\tilde{D}_j \notin \mathcal{A}(Y_{+\tilde{\varepsilon}}), \quad \forall\, j \in \mathcal{J}_+. \tag{37}$$

Let us define $\delta_j = d_i - \tilde{d}_j \geq 0$, $\forall\, j \in \mathcal{J}_-$, then $\tilde{D}_j = D_{-\delta}(0, d_i - \delta_j)$ and application of lemma 4 implies

$$\tilde{D}_j \notin \mathcal{A}(Y_{+\tilde{\varepsilon}}), \quad \forall\, j \in \mathcal{J}_-. \tag{38}$$

The relations (37) and (38) together with (34) lead to

$$\tilde{D}_j \notin \mathcal{A}(Y_{+\tilde{\varepsilon}}), \quad \forall\, j \in \{1, \ldots, \tilde{k}\}.$$

This means that the point $Y_{+\tilde{\varepsilon}} \in \tilde{Y}\hat{Y}$ (see (36)) is not covered, which again contradicts the assumption (30) that $\{\tilde{D}_k\}_{k=1}^{\tilde{k}}$ is the solution of the sensor placement problem.

To summarize, we have shown that (31) holds. Since $\mathcal{M}_i \cap \mathcal{M}_j = \varnothing$, $\forall\, i \neq j$, (31) implies that $\tilde{k} \geq k^*$. Which means the the solution of the sensor placement problem (6)–(10) is optimal.

$\square$

Lemma 2. *In the notion of theorem 1 let consider fixed points X, Y, D, and constant $\hat{r}$. Then the following implication is true*

$$D \in \mathcal{A}(Y) \quad \Rightarrow \quad D \in \mathcal{A}(\tilde{Y}) \quad \forall\, \tilde{Y} \in YD. \tag{39}$$

Proof. By definition $D \in \mathcal{A}(Y) \Leftrightarrow |YX| - \hat{r} \geq |YD|$ (see fig. 2). Let us denote $\tilde{r} = |YX| - \hat{r}$, and point C: $|XC| = \hat{r}$, $|YC| = \tilde{r}$. Then

$$\mathcal{B}(X, \hat{r}) \cap \mathcal{B}(Y, \tilde{r}) = \begin{cases} \{C\}, & |YD| = \tilde{r}, \\ \varnothing, & |YD| < \tilde{r}. \end{cases}$$

This indicates the applicability of lemma 1, hence $|\tilde{Y}X| - \hat{r} \geq |\tilde{Y}D|$, which by definition means that $D \in \mathcal{A}(\tilde{Y})$. $\square$

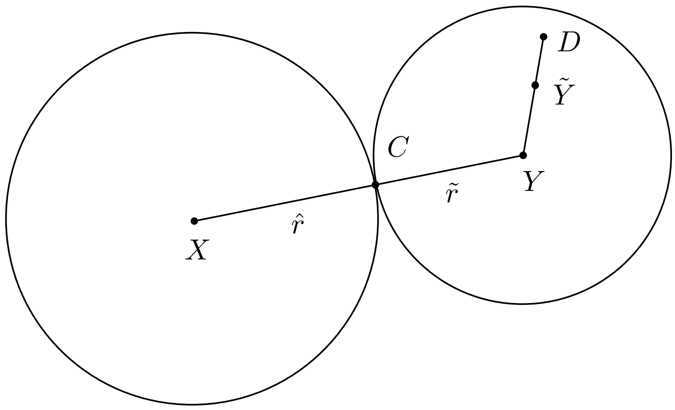

Figure 2: Illustration for lemma 2.

Lemma 3. *Let us denote* $D(0,d)$, $Y(0,y)$, $D_{+\delta}(0,d+\delta)$, $Y_{+\varepsilon}(0,y+\varepsilon)$. *Then the following implication is true*

$$D \in \overline{\mathcal{A}}(Y) \quad \Rightarrow \quad \forall\,\delta > 0\,\exists\,\hat{\varepsilon} = \hat{\varepsilon}(\delta) > 0 :\ D_{+\delta} \notin \mathcal{A}(Y_{+\varepsilon}) \quad \forall\,\varepsilon :\ 0 < \varepsilon \le \hat{\varepsilon}.$$

Proof. Let us fix any $\delta > 0$ and consider the function

$$f(\varepsilon) = \sqrt{x^2 + (y+\varepsilon)^2} - \sqrt{x^2 + y^2} + \varepsilon - \delta.$$

The function $f(\cdot)$ is continuous in $\mathbb{R}$ and $f(0) < 0$. Hence, there exists $\tilde{\varepsilon} > 0$ such that:

$$f(\varepsilon) < 0, \quad \forall\,\varepsilon :\ 0 < \varepsilon \le \tilde{\varepsilon}. \tag{40}$$

Since $D \in \overline{\mathcal{A}}(Y)$, we have

$$\begin{gathered} |XY| - \hat{r} = |DY| \quad \text{and} \quad d > y \quad \Leftrightarrow \\ \sqrt{x^2+y^2} - \hat{r} = d - y \quad \Leftrightarrow \quad \sqrt{x^2+y^2} = \hat{r} + d - y. \end{gathered} \tag{41}$$

Let us denote $\hat{\varepsilon} = \min(\tilde{\varepsilon}, \delta)$ and fix any $\varepsilon :\ 0 < \varepsilon \le \hat{\varepsilon}$ then $\delta - \varepsilon \ge 0$ and

$$\begin{gathered} |XY_{+\varepsilon}| - \hat{r} < |D_{+\delta}Y_{+\varepsilon}| \quad \text{i.e.} \quad D_{+\delta} \notin \mathcal{A}(Y_{+\varepsilon}) \quad \Leftrightarrow \\ \sqrt{x^2 + (y+\varepsilon)^2} - \hat{r} < d + \delta - y - \varepsilon \quad \Leftrightarrow \\ \sqrt{x^2 + (y+\varepsilon)^2} < \hat{r} + d - y - \varepsilon + \delta \quad \Leftrightarrow \{(41)\} \Leftrightarrow \\ \sqrt{x^2 + (y+\varepsilon)^2} < \sqrt{x^2+y^2} - \varepsilon + \delta. \end{gathered}$$

The last inequality holds for the fixed ε since $0 < \varepsilon \le \tilde{\varepsilon}$ and since (40) is true. $\square$

Remark 2. Lemma 3 can be formulated in a symmetric way:

$$D \in \underline{\mathcal{A}}(Y) \quad \Rightarrow \quad \forall\, \delta > 0 \quad \exists\, \hat{\varepsilon} = \hat{\varepsilon}(\delta) > 0 :$$
$$D_{-\delta} \notin \mathcal{A}(Y_{-\varepsilon}) \quad \forall\, \varepsilon :\ 0 < \varepsilon \le \hat{\varepsilon}.$$

The proof is fully analogous to the one presented above.

Lemma 4. *Let $X(x,0)$, $Y(0,y)$, $Y_{+\varepsilon}(0,y+\varepsilon)$, $D_{-\delta}(0,d-\delta)$, $x > \hat{r} \ge 0$. Then the following implication is true*

$$D \in \underline{\mathcal{A}}(Y) \quad \Rightarrow \quad D_{-\delta} \notin \mathcal{A}(Y_{+\varepsilon}) \quad \forall\, \delta \ge 0, \quad \forall\, \varepsilon > 0.$$

Proof. Let us fix any $\delta \ge 0$ and consider the function

$$f(\varepsilon) = \sqrt{x^2 + (y+\varepsilon)^2} - \sqrt{x^2 + y^2} - \varepsilon - \delta$$

and its derivative

$$f'(\varepsilon) = \frac{y+\varepsilon}{\sqrt{x^2 + (y+\varepsilon)^2}} - 1 \le \frac{|y+\varepsilon|}{\sqrt{x^2 + (y+\varepsilon)^2}} - 1 < \{\, x > 0 \,\} <$$
$$\frac{|y+\varepsilon|}{\sqrt{(y+\varepsilon)^2}} - 1 = 1 - 1 = 0, \quad \forall\, \varepsilon \ne -y.$$

Together with the obvious equality $f'(-y) = -1$ it implies that

$$f'(\varepsilon) < 0 \quad \forall\, \varepsilon \in \mathbb{R}. \tag{42}$$

Since for all $\varepsilon \in \mathbb{R}$ function $f(\cdot)$ is continuously differentiable, from (42) and the fact that $f(0) = -\delta \le 0$ it follows that

$$f(\varepsilon) < 0 \quad \forall\, \varepsilon > 0. \tag{43}$$

The following relations hold

$$D \in \underline{\mathcal{A}}(Y) \quad \Rightarrow \quad |XY| - \hat{r} = |DY| \quad \text{and} \quad d < y \quad \Leftrightarrow$$
$$\sqrt{x^2 + y^2} - \hat{r} = y - d, \tag{44}$$

and $\forall\, \delta \ge 0$, $\forall\, \varepsilon > 0$ the following relations are equivalent

$$D_{-\delta} \notin \mathcal{A}(Y_{+\varepsilon}) \quad \Leftrightarrow \quad |XY_{+\varepsilon}| - \hat{r} < |D_{-\delta} Y_{+\varepsilon}| \quad \Leftrightarrow$$
$$\sqrt{x^2 + (y+\varepsilon)^2} - \hat{r} < y + \varepsilon - d + \delta \quad \Leftrightarrow \quad \{(44)\} \quad \Leftrightarrow$$
$$\sqrt{x^2 + (y+\varepsilon)^2} - \hat{r} < \sqrt{x^2 + y^2} - \hat{r} + \varepsilon + \delta.$$

The last inequality holds for all $\varepsilon > 0$ as it follows from (43). $\square$

Lemma 5. *Under the notation and assumptions of theorem 1, the following implication is true*

$$k^* \geq 2 \quad \Rightarrow \quad y_{k^*} < a.$$

Proof. Let us assume the contrary, then

$$y_{k^*} \geq a \quad \Rightarrow \quad \{(24),\, y_1 = -a\} \quad \Rightarrow \quad a \in [y_1,\, y_{k^*}].$$

Based on (25), either $D_k \in \mathcal{A}(\hat{Y})$, in case if $\hat{Y} \in Y_k D_k$, for some $k = 1, \ldots, k^* - 1$ (since $y_{k^*} < d_{k^*}$ hence $a \notin (y_{k^*}, d_{k^*}]$ and this interval can be excluded), or still $D_k \in \mathcal{A}(\hat{Y})$, in case if $\hat{Y} \in D_k Y_{k+1}$, for some $k = 1, \ldots, k^* - 1$. This leads to the conclusion that

$$\exists\, \hat{k} \in \{1, \ldots, k^* - 1\} : \quad D_{\hat{k}} \in \mathcal{A}(\hat{Y}),$$

which means that $d_{\hat{k}} \geq a - r_0$ and $\hat{k} < k^*$, which contradicts (10). □

Let us generalize the definition of tsunamigenic point coverage for infinite points. We will say that a detector D is *covering a tsunamigenic point* $Y_{-\infty}(0, -\infty)$ $[Y_{+\infty}(0, +\infty)]$ if $\exists\, y_* : \forall\, y < y_*$ $[y > y_*]$ $D \in \mathcal{A}(Y(0, y))$. Taking this generalized definition into account, the definition of a detector covering an infinite tsunamigenic point from above (and below) remains the same as before.

Remark 3. Now we have defined in particular $D \in \overline{\mathcal{A}}(Y_{-\infty})$ and $D \in \underline{\mathcal{A}}(Y_{+\infty})$. Let us show that $\nexists\, D \in \underline{\mathcal{A}}(Y_{-\infty})$ and $\nexists\, D \in \overline{\mathcal{A}}(Y_{+\infty})$.

Let us assume that $\exists\, D(0, d) \in \overline{\mathcal{A}}(Y_{+\infty})$, that means that $|XY| - \hat{r} \geq |YD|$ $\forall Y(0, y) : y > y_*$ and at the same time $\forall \delta > 0$ $D_{+\delta}(0, d+\delta) \notin \mathcal{A}(Y_{+\infty})$ i.e.

$$\forall\, n \in \mathbb{N} \quad \exists\, Y_n(0, y_n) : \; y_n > n \quad \text{and} \quad |XY_n| - \hat{r} < |Y_n D_{+\delta}|.$$

Let us first fix some $\delta > 0$. Then let us fix some big enough n: $n > y_*$ and $n > d + \delta$. Then $y_n > y_*$ and $y_n > d + \delta$, hence

$$\begin{aligned} |XY_n| - \hat{r} &\geq |Y_n D| \\ |XY_n| - \hat{r} &< |Y_n D_{+\delta}|, \end{aligned}$$

which leads to

$$y_n - d = |y_n - d| = |Y_n D| \leq |XY_n| - \hat{r} < |Y_n D_{+\delta}| = |y_n - d - \delta| = y_n - d - \delta,$$

implying $\delta < 0$, which contradicts our initial assumption. Hence, $\nexists\, D \in \overline{\mathcal{A}}(Y_{+\infty})$. The fact that $\nexists\, D \in \underline{\mathcal{A}}(Y_{-\infty})$ can be shown analogously.

Theorem 2 (Infinite line in A-problem)**.** *Let a Cartesian coordinate system is defined on a plane, a settlement is located at the point* $X(x,\, 0)$ *and the tsunamigenic zone is represented by the* Y*-axis:* $\mathcal{Z} = \tilde{Y}\hat{Y}$*, where* $\tilde{Y}(0, -\infty)$ *and* $\hat{Y}(0, +\infty)$*. Let the constant wave spread velocity is* v *and the required lead warning time is* t_w *such that* $x > vt_w$*. Let* $\hat{r} = vt_w$ *and*

$$\begin{aligned} d_1 &= -\hat{r}, & (45)\\ d_{k+1} &= d_k + 2r_k, & (46)\\ r_k &= \frac{x^2 + d_k^2 - \hat{r}^2}{2(\hat{r} - d_k)}, & (47)\\ k^* &: d_{k^*} \geq \hat{r}, & (48)\\ & \quad d_k < \hat{r} \quad \forall\, k < k^*. & (49)\end{aligned}$$

Then the solution of the tsunami sensors placement problem exists, and the placement of k^* *tsunami detectors* $D_k(0, d_k)$ *described in the form* (45)–(49) *is optimal.*

Proof. Similarly to the proof of (18) it can be shown that under the conditions of this theorem the following upper assessment of k^* is true

$$k^* \leq \frac{\hat{r}}{\hat{\varepsilon}} + 1,$$

then k^* is limited from above, hence finite, and its definition in form of (48) and (49) is correct.

The only principal difference between theorem 1 and theorem 2 is the infinite points $\tilde{Y}$ and $\hat{Y}$. All the intermediate points $y_2, \ldots, y_{k^*}$ are finite (see (21)) since d_k $(k = 1, \ldots, k^*)$ are finite and r_k $(k = 1, \ldots, k^* - 1)$ are finite. So, to prove theorem 2, points $\tilde{Y}$ and $\hat{Y}$ need special handling. For the other points Y_k the same relations hold as in theorem 1.

Let us apply theorem 1 to the case where $a \to +\infty$. From (6) it follows that

$$d_1 = \sqrt{x^2 + a^2} - a - \hat{r}, \quad \text{and}$$

$$\lim_{a\to+\infty} \left(\sqrt{x^2+a^2} - a\right) = \lim_{a\to+\infty} a \left(\sqrt{\frac{x^2}{a^2}+1} - 1\right) =$$

$$\lim_{a\to+\infty} a \frac{\left(\sqrt{\frac{x^2}{a^2}+1} - 1\right)\left(\sqrt{\frac{x^2}{a^2}+1} + 1\right)}{\left(\sqrt{\frac{x^2}{a^2}+1} + 1\right)} =$$

$$\frac{1}{2} \lim_{a\to+\infty} a \left(\frac{x^2}{a^2} + 1 - 1\right) = \frac{1}{2} \lim_{a\to+\infty} \frac{x^2}{a} = 0.$$

Hence

$$d_1 \to -\hat{r} + 0, \quad \text{when} \quad a \to +\infty. \tag{50}$$

Let us show that

$$D_1 \in \overline{\mathcal{A}}(\tilde{Y}) \quad \text{and} \quad D_1 \in \mathcal{A}(Y) \quad \forall\, Y \in \tilde{Y} D_1. \tag{51}$$

The second relation is true since $\forall\, y \leq -\hat{r}$ the following relations hold

$$|XY| - \hat{r} \geq |YD| \quad \Leftrightarrow \quad \sqrt{x^2+y^2} - \hat{r} \geq -\hat{r} - y \quad \Leftrightarrow$$
$$\sqrt{x^2+y^2} \geq -y \quad \text{(true)}.$$

By taking into account (50) we also can say that $D_1 \in \overline{\mathcal{A}}(\tilde{Y})$, because for all $\delta > 0$ $D_{+\delta} \notin \mathcal{A}(\tilde{Y})$ since there exist $\hat{\delta}$: $0 < \hat{\delta} < \delta$ such that $D_{+\hat{\delta}} \in \overline{\mathcal{A}}(Y(0,\hat{a}))$ for some big enough $\hat{a}$ (and for that δ and $\hat{a}$ hence $D_{+\delta} \notin \mathcal{A}(Y(0,\hat{a}))$).

Analogously, one can show that

$$D_{k^*} \in \mathcal{A}(\hat{Y}) \quad \text{and} \quad D_{k^*} \in \mathcal{A}(Y) \quad \forall\, Y \in D_{k^*}\hat{Y}. \tag{52}$$

The relations (51) and (52) imply that (25) (equation (a) for $k = 1$) and (28) hold and the application of lemma 2 is not needed for infinite points. Lemma 3 is still suitable in this case since it applies in (35) for finite points. Lemma 4 applies in (38) for finite points and hence is still suitable. Lemma 5 is not needed under the conditions of this theorem since for infinite line the condition (36) is always true.

Taking into account spatial symmetry and (51), one may write $\hat{D}(0,\hat{r}) \in \underline{\mathcal{A}}(\hat{Y})$. According to lemma 6 $D(0,d) \in \mathcal{A}(\hat{Y})$ for all $d > \hat{r}$. Now the stopping rule (48), (49) is justified and the proof of the theorem 1 can be exactly followed to prove this theorem. $\square$

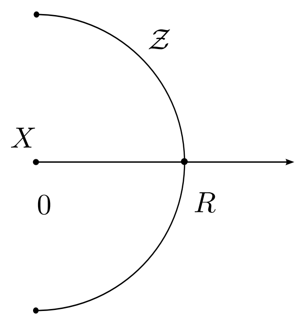

Figure 3: Half-circular tsunamigenic zone.

Lemma 6. *The following implication is true*

$$D(0,d) \in \mathcal{A}(Y_{+\infty}) \quad \Rightarrow \quad D_{+\delta}(0, d+\delta) \in \mathcal{A}(Y_{+\infty}) \quad \forall\, \delta > 0.$$

Proof. By definition

$$D(0,d) \in \mathcal{A}(Y_{+\infty}) \quad \Rightarrow \quad \exists\, y_* : \quad |XY| - \hat{r} \geq |YD| \quad \forall\, y > y_*.$$

Let us fix any $\delta > 0$ and fix any $\tilde{y}_* > \max(d+\delta, y_*)$ then

$$|XY| - \hat{r} \geq |YD| = y - d > y - d - \delta = |YD_{+\delta}| \quad \forall\, y > \tilde{y}_*.$$

That means by definition $D_{+\delta}(0, d+\delta) \in \mathcal{A}(Y_{+\infty})$. □

8.2 B-problem

Let us consider (see fig. 3) a plane with a polar coordinate system, a settlement located at $X(0,0)$, and tsunamigenic zone having the form of a half-circle

$$\mathcal{Z} = \{\, (\rho, \alpha) : \ \rho = R, \ \alpha \in [-\frac{\pi}{2}, \frac{\pi}{2}] \,\}. \tag{53}$$

Let us fix any detector D and any point $Y \in \mathcal{Z}$. Then, since $|XY| \equiv R$, the timely warning condition (20) will turn into

$$r \geq |DY|, \quad r = R - \hat{r}. \tag{54}$$

Let us denote $\mathcal{D}(D) = \{\, Y \in \mathcal{Z} : \ D \in \mathcal{A}(Y) \,\}$ – the set of points on the tsunamigenic zone covered by detector D. Taking into account (53) and (54) we may represent $\mathcal{D}(D)$ in the form of the following intersection

$$\mathcal{D}(D) = \mathcal{Z} \cap \mathcal{B}(D, r),$$

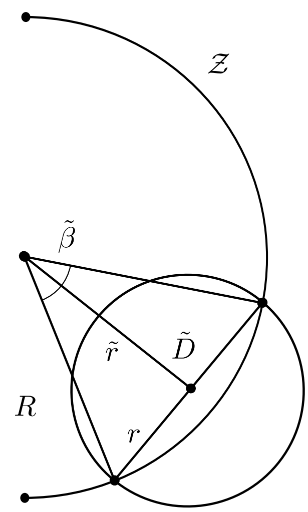

Figure 4: Detector coverage in B-problem.

which is an arc. Let us fix any $\alpha \in [-\frac{\pi}{2}, \frac{\pi}{2}]$ and consider a detector $D(d, \alpha)$. From geometrical considerations it is obvious that this arc has a maximum length if and only if D is located on the center of a horde of the length $2r$ in the half-circle $\mathcal{Z}$ (see fig. 4), i.e. when $d = \sqrt{R^2 - r^2}$. We will re-formulate that fact in the form of the following

Lemma 7. *Under the notation of section 8.2 a detector $D(d, \alpha)$ is covering an arc of $\mathcal{Z}$ not greater than the detector $\tilde{D}(\tilde{r}, \alpha)$, where $\tilde{r} = \sqrt{R^2 - r^2}$.*

Theorem 3 (Optimal solution in B-problem)**.** *Let $X = 0 \in \mathbb{R}^2$, $\mathcal{Z}$ is defined according to* (53)*, and $R > \hat{r}$. Then the solution of the tsunami sensors placement problem exists, and the following placement of k^* tsunami detectors D_k is optimal:*

$$D_k = D(\tilde{r}, -\frac{\pi}{2} + (k - \frac{1}{2})\tilde{\beta}), \tag{55}$$

$$\textit{where} \quad \tilde{\beta} = 2 \arcsin \frac{r}{R}, \quad \tilde{r} = \sqrt{R^2 - r^2}, \quad r = R - \hat{r},$$

$$k = 1, \ldots, k^*, \quad k^* = \left\lceil \frac{\pi}{\tilde{\beta}} \right\rceil.$$

Proof. Detector D_1 is covering the entire arc $[-\frac{\pi}{2}, -\frac{\pi}{2} + \tilde{\beta}]$ (see fig. 4 and lemma 7), analogously, detector D_k is covering the entire arc $[-\frac{\pi}{2} + \tilde{\beta}(k -$

$1), -\frac{\pi}{2} + \tilde{\beta}k], \forall\, k = 1, \dots, k^*$. Since $k^* \geq \frac{\pi}{\tilde{\beta}}$ then

$$-\frac{\pi}{2} + \tilde{\beta}k^* \geq -\frac{\pi}{2} + \tilde{\beta}\frac{\pi}{\tilde{\beta}} = \frac{\pi}{2},$$

and the entire arc $[-\frac{\pi}{2}, \frac{\pi}{2}]$ is covered by detectors $\{D_k\}_{k=1}^{k^*}$. Hence, this set of detectors is the solution of the tsunami sensors placement problem and the existence of the solution is proved.

Let us show now the optimality. Let us consider any detectors placement $\{\hat{D}_j\}_{j=1}^{\hat{k}}$ such that $\hat{k} < k^*$. Since each detector D_j is covering the arc not greater than $\tilde{\beta}$ (see lemma 7 and fig. 4), then the $\hat{k}$ detectors cover together the arc not larger than

$$\tilde{\beta}\hat{k} < \tilde{\beta}k^* \leq \tilde{\beta}\frac{\pi}{\tilde{\beta}} = \pi,$$

which means the arc $\mathcal{Z}$ having the length $\pi = \frac{\pi}{2} - (-\frac{\pi}{2})$ is not covered. This means that $\{\hat{D}_j\}_{j=1}^{\hat{k}}$ is not a solution and the optimality is proved. $\square$

— — — — —

Theorem 4. *The number of detectors in both A-problem and B-problem depends only on the scalar parameter*

$$\alpha = \frac{x}{\hat{r}}, \tag{56}$$

where in the B-problem $x = R$.

Proof. This statement is obvious in case of the B-problem, since from (55) it follows that

$$k^* = \left\lceil \frac{\pi}{2\arcsin(1 - 1/\alpha)} \right\rceil. \tag{57}$$

In case of the A-problem taking into account (45)–(49) and (56) in the form of $x = \alpha\hat{r}$, the following equalities are true

$$d_1 = -\hat{r},$$
$$r_1 = \frac{(\alpha\hat{r})^2 + \hat{r}^2 - \hat{r}^2}{2(\hat{r} + \hat{r})} = \frac{\alpha^2}{4}\hat{r}.$$

So, we have the dependence of d_1 and r_1 on parameter α in the form

$$d_1 = f_1(\alpha)\hat{r}, \quad f_1(\alpha) = -1,$$
$$r_1 = g_1(\alpha)\hat{r}, \quad g_1(\alpha) = \frac{\alpha^2}{4},$$

here it can be noted that variables α and $\hat{r}$ are separable. Let us assume that

$$d_k = f_k(\alpha)\hat{r}, \tag{58}$$
$$r_k = g_k(\alpha)\hat{r}, \tag{59}$$

and show that variables α and $\hat{r}$ are separable for $k+1$, i.e.

$$d_{k+1} = f_{k+1}(\alpha)\hat{r}, \quad \text{if} \quad k \le k^* - 1,$$
$$r_{k+1} = g_{k+1}(\alpha)\hat{r}, \quad \text{if} \quad k < k^* - 1.$$

From (45)–(49) it follows that the following equalities are true

$$d_{k+1} = d_k + 2r_k = [f_k(\alpha) + 2g_k(\alpha)]\hat{r} \equiv f_{k+1}(\alpha)\hat{r},$$
$$r_{k+1} = \frac{(\alpha\hat{r})^2 + f_{k+1}^2(\alpha)\hat{r}^2 - \hat{r}^2}{2(\hat{r} - f_{k+1}(\alpha)\hat{r})} \equiv g_{k+1}(\alpha)\hat{r}.$$

Here we have denoted

$$f_{k+1}(\alpha) = f_k(\alpha) + 2g_k(\alpha) \quad \text{and} \quad g_{k+1}(\alpha) = \frac{\alpha^2 + f_{k+1}^2(\alpha) - 1}{2(1 - f_{k+1}(\alpha))}.$$

Now (58) is prooved for all $k = 1, \ldots, k^*$ and (59) is proved for all $k = 1, \ldots, k^* - 1$. The conclusion coming out of that is that the optimal (minimal) number of detectors k^* depends only on the single parameter α, since the stopping rule (48)–(49) can be re-written in the form

$$f_{k^*}(\alpha) \ge 1, \quad \text{and} \quad f_k(\alpha) < 1, \quad \forall\, k < k^*.$$

Now the case of A-problem is analyzed and the theorem is fully proved. □

Remark 4. For the purposes of optimal number of sensors calculation given the constant wave spread velocity, theorem 4 provides the way to replace two basic parameters – the lead warning time and the distance to a tsunamigenic zone – with one aggregated parameter α.

Theorem 5. *In A- and B-problems the optimal number of detectors have the following respective asymptotic assessments for* $\alpha \to 1 + 0$

$$\frac{2}{3\sqrt{\alpha - 1}} + \underline{O}(\sqrt{\alpha - 1}) \le k_A^*(\alpha) \le k_B^*(\alpha), \tag{60}$$
$$k_B^*(\alpha) = \frac{\pi}{2}(\alpha - 1)^{-1} + \underline{O}(1). \tag{61}$$

Here $\underline{O}(1)$ *denotes some function uniformly limited by absolute value for all values of* $(\alpha - 1)$ *close enough to 0, and* $\underline{O}(x)$ *denotes some function* $f(x)$ *such that* $f(x)/x = \underline{O}(1)$ *for all* x *close enough to 0.*

Proof. For the B-problem a Taylor series expansion of (57) for $\alpha \to 1$ immediately leads to (61).

Let us consider the A-problem. From lemma 8 immediately follows the right-hand side inequality of (60). According to theorem 4 the optimal number of detectors depends only on α and not on absolute values of x or $\hat{r}$. Let assume $\hat{r} = 1$ then $x = \alpha = \alpha\hat{r}$, $\alpha \to 1 + 0$, $x \to \hat{r} + 0$. Let introduce a constant $a = \sqrt{\alpha - 1}$ and consider an A-problem for the finite segment $[-a, a]$ further referred to as A_α. Obviously,

$$k_A^*(\alpha) \geq k_{A_\alpha}^*, \tag{62}$$

since $\mathcal{Z}_A \supseteq \mathcal{Z}_{A_\alpha}$ i.e. if a sensor network $\{D_k\}$ is covering $\mathcal{Z}_A$ then of course $\{D_k\}$ is covering $\mathcal{Z}_{A_\alpha}$. According to lemma 9, $r_k \leq r_0 \quad \forall\, k < k^* \equiv k_{A_\alpha}^*$ then from (7) it follows that

$$d_{k+1} = d_k + 2r_k \leq d_k + 2r_0$$

that leads to

$$d_{k+1} \leq d_1 + k2r_0$$

which together with (9) in the form of $d_{k^*} \geq -d_1$ implies

$$\begin{aligned} -d_1 \leq d_{k^*} \leq d_1 + (k^* - 1)2r_0 \quad &\Leftrightarrow \quad -2d_1 \leq (k^* - 1)2r_0 \quad \Leftrightarrow \\ k^* - 1 \geq -\frac{d_1}{r_0} \quad &\Leftrightarrow \quad k^* \geq -\frac{d_1}{r_0} + 1. \end{aligned} \tag{63}$$

The term $-\frac{d_1}{r_0}$ using (6) and Taylor series expansion can be represented in the form

$$-\frac{d_1}{r_0} = \frac{a - r_0}{r_0} = \frac{a}{r_0} - 1 = \frac{\sqrt{\alpha - 1}}{\sqrt{\alpha^2 + \alpha - 1} - 1} - 1 = \frac{2}{3\sqrt{\alpha - 1}} - 1 + \underline{O}(\sqrt{\alpha - 1}),$$

which together with (63) and (62) leads to the left-hand inequality in (60). Now the theorem is fully proved. $\square$

Lemma 8. *Let a settlement is located at $X = 0 \in \mathbb{R}^2$ and tsunamigenic zones in A-problem and B-problem are respectively*

$$\begin{aligned} \mathcal{Z}_A &= \{\, (x, y) \ : x = R \,\}, \\ \mathcal{Z}_B &= \{\, (x, y) \ : x^2 + y^2 = R^2,\ x \geq 0 \,\}. \end{aligned}$$

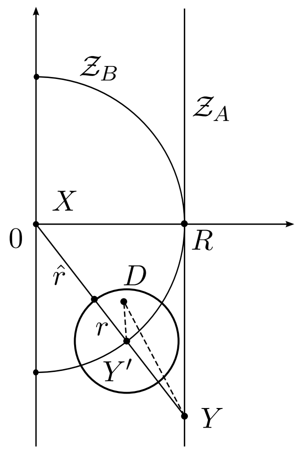

Figure 5: Half-circular and linear tsunamigenic zones.

Let $\hat{r} < R$ and k_A^*, k_B^* are the optimal number of detectors in A-problem and B-problem respectively. Then the following inequality holds

$$k_A^* \leq k_B^*.$$

Proof. Let us fix any $Y \in \mathcal{Z}_A$ and denote $Y' = XY \cap \mathcal{Z}_B$ (see fig. 5). Let $\{D_k\}$ is a solution of the B-problem, then

$$\exists\, D \in \{D_k\} \; : \quad |XY'| - \hat{r} \geq |DY'| \quad \text{and then}$$
$$|XY| - \hat{r} = |XY'| + |YY'| - \hat{r} \geq |DY'| + |YY'| \geq |DY|,$$

hence the point Y is covered by the detector D. The conclusion holds for any point $Y \in \mathcal{Z}_A$, hence the sensor network $\{D_k\}$ provides timely warning in the A-problem. So, any solution of the B-problem is the solution of the A-problem, hence optimal solution in A-problem cannot have more sensors than that in B-problem and the lemma is proved. □

Lemma 9. *In the placement of sensors* (6)–(10) *the following inequality holds*

$$r_k \leq r_0 \quad \forall\, k < k^*.$$

Proof. From (6), (10), and (14) it follows that

$$|d_k| \leq a - r_0 = \{\, \sqrt{x^2 + a^2} \equiv b \,\} = a - b + \hat{r}, \quad \forall\, k < k^*. \tag{64}$$

Taking into account the newly introduced variable b one may write

$$r_0 = b - \hat{r}. \tag{65}$$

Now based on (8) and (64) for all $k < k^*$ the following chain of relations is true

$$
\begin{aligned}
r_k = & \frac{x^2 + d_k^2 - \hat{r}^2}{2(\hat{r} - d_k)} \leq \frac{x^2 + (a - b + \hat{r})^2 - \hat{r}^2}{2(\hat{r} - a + b - \hat{r})} = \\
& \frac{x^2 + (a - b + \hat{r})^2 - \hat{r}^2}{2(b - a)} = \frac{x^2 + (a - b)^2 + 2\hat{r}(a - b) + \hat{r}^2 - \hat{r}^2}{2(b - a)} = \\
& \frac{x^2 + (a - b)^2 + 2\hat{r}(a - b)}{2(b - a)} = \frac{1}{2}(b - a) - \hat{r} + \frac{x^2}{2(b - a)} = \\
& b - \hat{r} - \frac{1}{2}(b + a) + \frac{x^2}{2(b - a)} = \{\ (65)\ \} = r_0 + \frac{x^2 - (b + a)(b - a)}{2(b - a)} = \\
& r_0 + \frac{x^2 - b^2 + a^2}{2(b - a)} = r_0 + \frac{x^2 - x^2 - a^2 + a^2}{2(b - a)} = r_0,
\end{aligned}
$$

which proves the lemma. □

9 Bibliography

[put a web link to the ANI model]

The Benefit of High Resolution Aerial Imagery for Topographic Mapping and Disaster Recovery: Lessons Learnt from the 2004 Indonesian Tsunami

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1 Introduction

This research outlines a case study in Aceh, Indonesia, in the aftermath of the December 2004 Indian Ocean Tsunami. The main aim of the study was to identify methods to determine and quantifiably assess the benefit of the use of a specific spatial data set in disaster recovery, and it follows on from an earlier study implemented in 2007.

The earthquake and subsequent Tsunami devastated wide areas and hundreds of communities across Aceh. The available topographic data (i.e. relief and the spatial location of man-made and natural features) was approximately 30 years old and contained significant errors. Immediately after the Tsunami there was a large demand for new topographic and spatial data to support the rehabilitation and reconstruction activities, including; the needs of the national Government master plan for reconstruction, the spatial planning needs of local Government, town and village action plans, community based mapping, village development mapping, infrastructure services, and disaster, hazard and risk mapping.

During 2005, the Government of Indonesia (GoI), in conjunction with a number of Official Development Agencies (ODA's), initiated at least 10 projects for the capture of spatial data and the provision of updated topographic data and products to the rehabilitation and reconstruction community. This case study focuses on the benefit derived from a dataset of high resolution (25 cm) digital aerial imagery (orthophotos) acquired across the Tsunami affected areas in Aceh.

The results of a detailed data user survey implemented two years after the Tsunami are also presented. They clearly demonstrate the need and the benefit of the use of this data for disaster recovery, showing that this data set critically supported projects worth 28 million Euro and provided further support to projects worth over 880 million Euro. A simple robust methodology quantifying the benefit of the use of spatial data in disaster recovery is also presented. The methodology provides a monitoring mechanism by which the benefit of using the spatial data can be quantified, verified and accounted to either donor or user communities

Finally, to ensure that any spatial data acquisition campaign undertaken with humanitarian funding is used to its greatest benefit, a number of recommendations detailing mechanisms that must be in place prior to initiation of the campaign are presented.

2 Overview of NORAD Campaign and data set

The Norwegian Agency for International Development (NORAD) funded the orthophoto project, at a cost of 1.43 M Euro, in March 2005. The Indonesian National Coordinating Agency for Surveys and Mapping (Bakosurtanal) managed the project and made all products available to the recovery community. The products included a digital terrain model (DTM), and digital orthophotos merged into a digital base map with line mapping at 1:10,000 and 1:5,000 map scales. The extent of the data set, totalling 6,249 km^2 across the Tsunami affected coastal areas, is shown in Figure 1

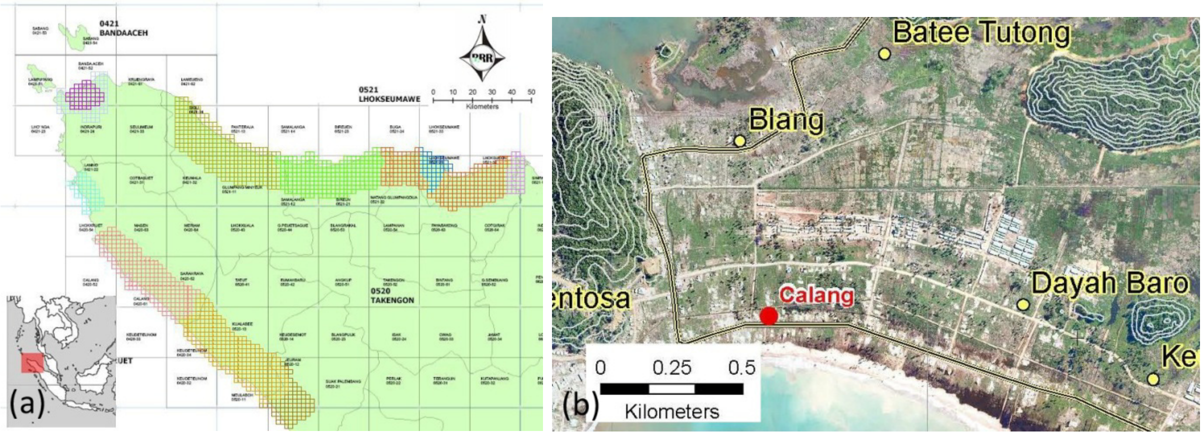

Figure 1 (a) Location and extent of orthophotos and digital terrain model, and (b) example of orthophoto and contour lines, extracted from DTM, showing temporary shelters in Calang (East Coast Aceh)

Delays, due to security clearance and permission to fly, meant the flight campaign was only completed in July 2005. All final products were completed and delivered to Bakosurtanal in April 2006. With the exception of the DTM, Bakosurtanal provided all products in August 2006 to the Spatial Information & Mapping Centre, (SIM-Centre) of the GoI Agency for Rehabilitation and Reconstruction of NAD and NIAS (BRR), for distribution to the aid and recovery community (users).

The data set was distributed in three ways, either; (case 1) directly as an electronic data set to users; (case 2) provided as a customised product; or (case 3) enabled for users electronically via web applications. Primary data users (case 1) were given digital (soft) copies of the data set and were bound by a signed data user agreement. During the period August 2006 to July 2008 there was a total of 99 recorded primary data users and over 635 secondary data users (cases 2 and 3). The data set was also used as a core data in Geographic Information System (GIS) training provided to at least 500 local government officials.

3 Example case studies on data use

To justify their requirement for the use of the data set, all primary data users were obliged to provide project details, which were confirmed with an independent project registration maintained within the Recovery Aceh Nias Database (RAND) of the BRR. The requests for the data set, as is shown in Figure 2a, covered the spectrum of all agencies within the recovery and rehabilitation community. Examples of data usage are presented in the following section.

3.1 Asian Development Bank (ADB)

The Earthquake and Tsunami Emergency Support Project (ETESP) of the ADB used the data set in four of their projects. The data was used to support their Spatial Planning and Environmental Management project, Agriculture Sector, Fisheries Sector and Road and Bridges project. Specifically the projects oversaw the preparation of sub-district level Action Plans; the rehabilitation and reconstruction of livelihoods assets post Tsunami in both agriculture and fisheries sectors; support to fisheries rehabilitation in Aceh and Nias and the creation of the design and project preparation documents for road segments within Banda Aceh and on the East coast. The four projects had over 125,000 direct beneficiaries and cost a total of over 79 Million Euro. The data set was used to some extent, in all five phases of each project's lifecycle (i.e. project initiation, planning, operation, monitoring and evaluation and project closure), but was most significantly used in the operational phase of the projects. Over 85 maps were created within the projects from the case study data set and GIS data sets provided.

3.2 United Nations Development Programme (UNDP)

The UNDP through its Tsunami Recovery Waste Management Programme (TRWMP) began the program for Agriculture land clearances in January 2006.It removed the heavy deposits of sand, silt and debris blanketing the land, and blocking the irrigation channels and drains. The program cost over 1.5 million Euro and supported 2600 families as direct beneficiaries. The TRWMP used numerous spatial data sets, including the orthophoto data set, to locate areas in greatest need of land clearance, and to work with farmers and community leaders to demark field boundaries, canals and drains.

The orthophoto data set was used as a primary mapping tool to determine areas and potential volumes of waste that required removal and to prepare clearance plans. This information was critical for preparation of heavy equipment contracts required for land clearance. The data set was critically used for project planning, operation and monitoring and evaluation and is estimated that it would cost approximately 200,000 Euro to obtain the same information from different sources.

4 Data user survey

To asses the benefit of the orthophoto data, a data user survey was undertaken in Aceh, during 2008. The survey, delivered as a questionnaire, was distributed to all primary data users. To encourage a high response rate, the survey was intentionally simple and brief. It was designed to retrieve information to determine answers to the following study questions:

- Which category of organisation were the main users of the data set?
- What type of project required the data set and how was it used?
- At which phase of the project life cycle was the data set most significant?
- What was the benefit of using the data set?
- What were the problems with the data set?

One of four outcomes were expected from each questionnaire; 1) no response; 2) data set was acquired by user but not used in project; 3) data set was acquired and used but its use was not critical to the successful completion or operation of the project (supported the project); 4) data set was acquired and used and its use was critical to the successful completion or operation of the project. Follow up with all primary data users ensured a relatively high questionnaire response rate (48%).

Two methods were identified to provide a simple means of quantifying the benefit of the use of the data set. The first method uses a project attribute as an indicator of the measure of the overall benefit of the project and also determines if the use of the case study data was critical to the successful completion of the project. The second method considers what information was obtained by using the data set and determines the real cost to acquiring that information from another source. This real cost was only calculated where the use of the data set was deemed to be critical to the successful completion or operation of the project.

5 Results of data user survey

As shown in Figure 2b, NGO's were the most significant data users. Using the standardised DAC5 coding (Development Assistance Committee Coding Scheme 5) to categorise project type, the data, as shown in Figure 3a, was mainly used for Urban and Rural planning purposes (52%).

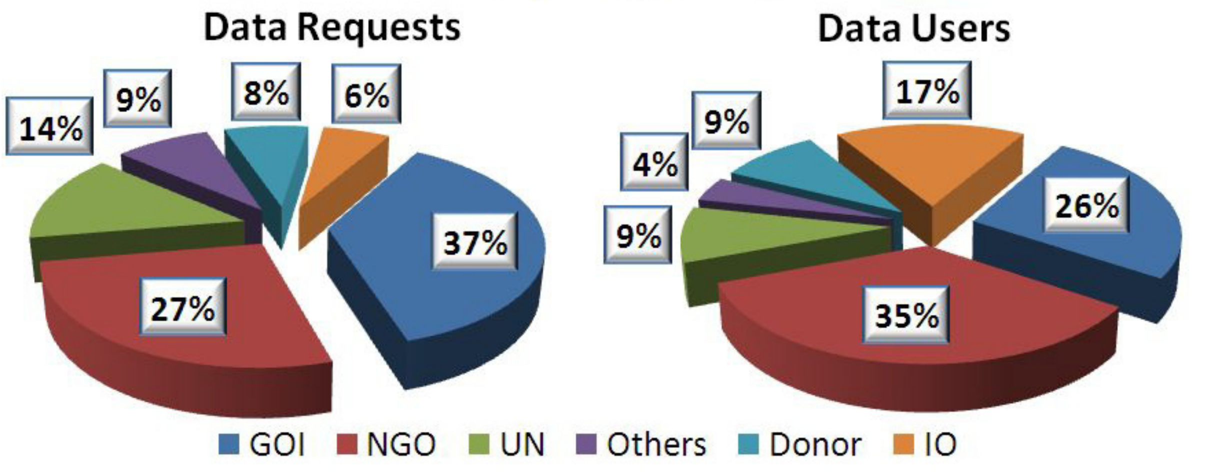

Figure 2(a) Orthophoto data requests and (b) data users by Agency Type including; Government of Indonesia (GOI); Non Governmental Organisations (NGO); United Nations (UN); and International Organisations (IO)

In all projects the data was used largely for mapping, surveying or identification of features relevant to each of the projects; 95% of the respondents claimed to use the case study data over 300 times to produce maps, and a further 65% claimed to integrate the case study data within a GIS.

	Project Phase				
	Initiation	Planning	Operation	Monitoring & Evaluation	Closure
Percent Usage (%)	74	92	87	70	78
Relative Importance (1-high to 5-low)	3.1	1.6	1.3	2.5	3.1

Table 1 Use and importance of data in project phases (1 important, 5 not important)

The majority of projects used the data in the planning and operational phases of the project, noting that the data was considered to be of most importance during these project phases (see Table 1)

The main concern highlighted by the primary users was that the data was not available for the project planning phase of projects starting before August 2006. Considering the rapid developments in rehabilitation and reconstruction in the Tsunami affected areas, the data, acquired in June 2005, was largely outdated by the time it was delivered to the rehabilitation and reconstruction community

6 Determination of the benefit of use of orthophoto data

6.1 Calculated by project attribute

Four project attributes were identified as potential indicators of project benefit; 1) number of direct project beneficiaries (i.e. number of families, or number of persons, that would receive a direct improvement in their current situation as a result of the completion of the project); 2) physical extent and coverage of the project area; 3) information on the total cost of the project, and; 4) information on the duration of the project.

The most incomplete and overestimated attribute was project beneficiary, with only 39% of primary users being able to provide a figure; several wildly claiming their project benefited all the 4,031,589[1] residents in the province of Aceh, or all of the estimated 203,998 people who were directly affected by the Tsunami. A similar response was found for the attribute concerning the physical extent of the project. The attribute for duration of project was the most comprehensibly reported upon by 91% of respondents. This attribute was initially included to ascertain if longer running projects had a greater benefit, or if there was a direct link between project duration and project cost.

Finally, the attribute of project cost was selected to measure the benefit of the use of the data set as this attribute was widely reported by the respondents (87%), and could be independently confirmed by cross checking with the RAND of the BRR. When the use of the data set was deemed critical to the completion or operation of the project, then the benefit of the use of the data set was measured as the total cost of the project, Figure 3b.

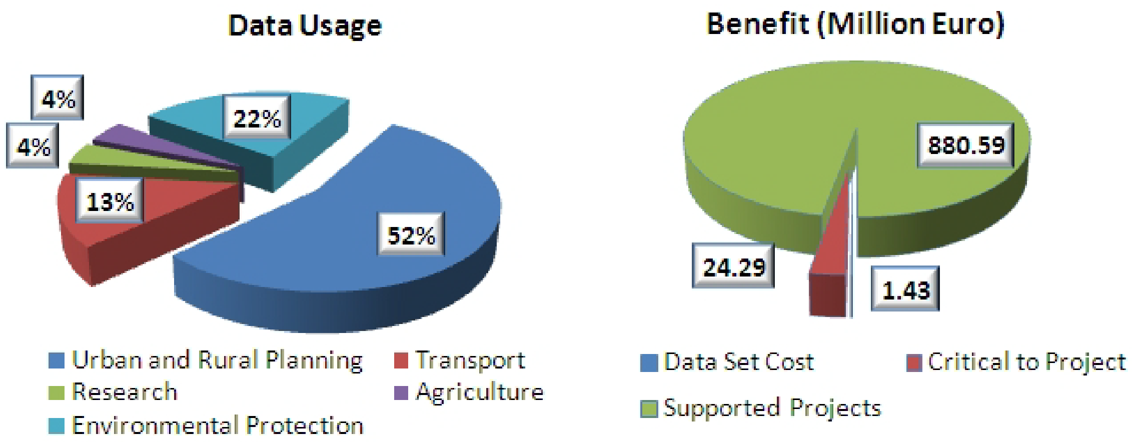

Figure 3(a) Data Usage and (b) Benefit of Data Set compared to Data Set Costs

6.2 Calculated by cost of equivalent information from a different source

If the data set was seen to be critical to the completion or operation of the project, the primary users were also asked to provide an estimated cost of retrieving the same information from another source. All cost estimations were independently verified, considering local conditions, cost and availability of other sources of information. The total cost to provide the same information as obtained from the data set was estimated to be 3.46 Million Euro. Since primary users failed to accurately report their project extent, it is not possible to make a direct area based comparison of obtaining the equivalent information, and therefore cannot be compared directly to the 1.43 Million Euro cost of the orthophoto project.

7 Conclusions

This study quantified the benefit of using the case study data set by determining if the use of the data set was critical to the successful completion of a project, and then using the attribute of project cost as a measure of its benefit. The data set critically supported projects worth over 16 times its actual cost and supported projects worth over 600 times its actual cost. Over 635 further secondary users of the data set were also clearly identified. The delayed delivery of the case study data set to the recovery community meant that the data could not be used for sectors of reconstruction projects that had an urgent and timely need for completion.

[1] Badan Pusat Statistik (Statistics Indonesia) BPS, Sensus Penduduk Aceh Nias (Census of Residents of Aceh and Nias) SPAN 2005

In order to determine and report upon the benefit of the use of spatial data in disaster recovery, the following recommendations are offered:

- A robust, straightforward procedure must be in place with the data distributor that records simple criteria for each of the data users and related projects;
- Updating of project information on a regular but limited basis must be enforced, and easily verifiable;
- Wherever possible, international standards such as the use of DAC5 code for project categorisation, should be included in the methodology

Whilst this report clearly shows that there is a need for the acquisition of EO data and the creation of spatial data in response to a disaster, a number of lessons have been learnt from the spatial data initiatives between ODA's and the GoI in response to the Tsunami in Aceh.

To ensure that the spatial data is used to its greatest benefit, it is specifically recommended that any spatial data campaign undertaken with humanitarian funding, must also ensure the following:

- A mechanism must be in place to ensure data is efficiently and effectively delivered to the humanitarian aid community in a timely manner;
- The mechanism must be open and accountable to data providers, donors and the recovery community;
- The humanitarian aid and recovery community must have knowledge about the availability of the data;
- To avoid duplication of costs, the spatial data must be freely accessible, (i.e. no cost, or data reproduction costs only), and with an unrestrictive license

8 Acknowledgements

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Value of Weather Observations for Reduction of Forest Fire Impact on Population

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Abstract – In this paper we investigate how improvements in the weather observation systems help to reduce forest fires impact on population by targeting and monitoring places where ripe fires are likely to occur. For the purposes of population impact assessment we suggest a relevant index. In our model the air patrolling schedule is determined by the Nesterov index, which is calculated from observed weather data sets at different spatial resolutions. The reduction of fire impact on population, associated with utilization of finer grid, indicates the benefits of more precise weather observations. We also explore the sensitivity of the forest fires model with respect to the quality of input data while taking into account the multitude of sources providing weather observations. Our model shows that approximately 90% of the feasible reduction of fire impact on population can be achieved by refining weather observations in 30% of the area of interest.

Keywords: forestry, fires, meteorology, population impact, societal benefits of Earth observations.

1. INTRODUCTION

Earth observation has been an integral part of managing human societies for millennia. In the 21st century mankind has substantially altered the major bio-geochemical cycles on global scales possibly augmenting risks emanating from changes in the behavior of the total Earth system. One of these new risks is linked to an increase in fire calamities, which possibly could cause negative feedbacks to the global carbon cycle, impair ecosystems functions, cause human casualties, and destroy valuable human assets. Thus, in order to attain sustainable development goals, the management of many observation subsystems in a coherent, efficient, and effective manner is needed. And for this purpose a comprehensive Global Earth Observation System of Systems should be implemented.

1.1 Motivation

The pathway of benefit generation for fire management, augmented by an Earth Observation System of Systems, is achieved through better informed and, therefore, improved decision making processes and more advanced fire management resulting in fewer burned areas and overall reduced net losses. Despite the practical importance of improved information for disaster prevention and response, the quantification of the "observation quality – benefits" relationship has not yet been performed with regard to the forest fires impact on population..

1.2 Aims

Our aim is to develop a model that would allow for a quantitative assessment of the value of improved observations for disaster response to forest fires. More specifically, we aim at obtaining quantitative results measuring the feasible reduction of forest fires-induced impact on population (including loss of life and property) that better Earth observations (EO) could contribute to. For that purpose we suggest an indicator measuring in an aggregated way the fire impact on population and perform an assessment of its reduction potential. Additional sub-goal is to explore the inter-dependence between the population impact and such natural indicator as burned areas. The research presented here is focused mainly on monitoring of the disaster-prone areas and early detection of fires. We employ simplified mathematical representation of other related processes, hence the detailed fire spread model and also fire extinguishing model are beyond the scope of this paper.

1.3 References to Related Work

The simplified forest fire index, which is at the core of the model we use, was originally suggested by Nesterov (1949). More sophisticated systems were developed with time, e.g. Van Wagner (1987). Nevertheless, Buchholz et al. (2000) show that application of simplified indices is still useful if the available information is limited to basic parameters. One of the applications of the Nesterov index to the Iberian Peninsula case study is presented by Venevsky et al. (2002). Fiorucci et al. (2004) explore a resource allocation problem for forest fire risk management. Khabarov et al. (2008) evaluate the importance of observations for reduction of burned areas. Some applications of remote sensing techniques to forest fire monitoring and risk assessment are presented in e.g. Saatchi et al. (2007), Yebra et al. (2008).

1.4 Overview

The next part of the paper sets the stage by introducing the fire impact on population index (FIPI) and a simple fire hazard model along with relevant data, forest patrolling rules and probabilities' assessment composing altogether the forest fire fighting model. Then, we articulate the methodology to assess in a quantitative manner the benefits of improved weather observations. Further, in the section 3, we focus on the sensitivity of the model with respect to the variation of the number of ground weather stations, and highlight the problem of the optimal observation system design. Section 4 concludes the paper.

2. MODEL AND DATA

The purpose of the model described below is to demonstrate how local population can benefit from the improvements to in-situ weather measurements. The effective use of air patrols for forest fire detection is at the model's core. As an example of the air patrolling rules, we utilize the rules developed in the Russian Federation, which are based on the Nesterov index. Some other forest fire danger assessment systems are presented in e.g. Van Wagner (1987) and Satoh et al. (2004). Nesterov index is used to assess fire danger on daily basis, and it is the basic indicator for

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decision making with regard to implementing particular measures to reduce possible losses due to forest fires. We calculate Nesterov index on two grids: (1) the original 'fine' grid and (2) the 'rough' grid with the spatial resolution decreased by factor 2. We pick up a small cell to represent weather data in bigger aggregated cell. Then we apply forest patrolling rules to calculate under otherwise equal conditions the losses in terms of the burned forest area and the total patrolled area for both 'fine' and 'rough' grids. After specifying the technical characteristics of an aircraft the total patrolled area can be easily converted into tons of fuel consumed for air patrol. The total cost of the burned area can be calculated based on the type of trees growing in the area, the distance from the roads/railways, the amount of CO_2 emissions caused by the fires, etc. Taking into account the population located in the area and possible damage caused by fires to the property and human health, including loss of life, we suggest to measure the fire impact on population by the following Fire Impact on Population Index (FIPI):

$$FIPI = BA / TA \times PD, \tag{1}$$

where *BA* is the yearly burnt area in a grid cell, *TA* is the total grid cell area, and *PD* is the population density in the grid cell (inhabitants per km^2). The FIPI reflects the number of people affected by fire per year per km^2.

For the calculations we chose the area covering parts of Spain and Portugal located approximately between -7.5W, 42.0N and -0.5W, 38.0N. The grid cell size is 50 x 50 km, see Figure 1. We have chosen this area only because of the availability of suitable weather data. We consider a simplified forest fire model aiming at developing an approach to assessment of the value of information for fighting forest fires. Using the same approach, the model constants and the set of forest fire patrolling rules can be adjusted to reflect real situation and practices in a particular region.

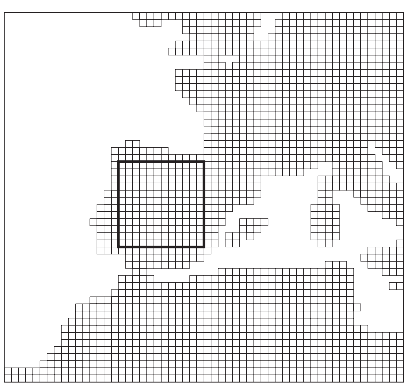

Figure 1. The dataset grid cells of the study area covering parts of Portugal and Spain.

We use a gridded weather dataset for the year 2000 containing daily temperature, precipitation, and vapor pressure (European Commission – Joint Research Centre (JRC) interpolated meteorological data source, JRC/AGRIFISH Data Base: http://mars.jrc.it/marsstat/datadistribution/). The formula for the calculation of the Nesterov index is

$$I(t) = \sum_{k=s}^{t} (t_k - t_k^d) \cdot t_k, \tag{2}$$

here t denotes day number since the start of observations, t_k is the daily temperature in Celsius degrees, t_k^d is the dew point temperature in Celsius degrees for the day k. If the precipitation is greater than 3 mm at a day number s-1, then the Nesterov index drops to zero and the summation restarts from the next day s.

2.1 Forest Fire Patrolling Rules

According to the actual value of the Nesterov index in a specific area the fire danger class is determined and corresponding air patrol frequency is applied to that area. Table A is officially used in Russia for that purpose. Below we show which implications that forest fires strategy coupled with observed weather data may have on the impact of forest fires on population in terms of FIPI.

Table A. Fire danger classes and air patrol frequency depending on Nesterov index

Nesterov index	Fire danger	Fire danger class	Air patrol frequency
≤ 300	—	I	No patrol
> 300	Low	II	Once in 2–3 days
> 1 000	Medium	III	Once daily
> 4 000	High	IV	Twice daily
> 10 000	Extreme	V	Three times a day

2.2 Probabilities Assessment

To assess the forest fire occurrence probability, we use the formulas proposed by Venevsky et al. (2002). The probability of a fire provided that there is an ignition in the area is calculated as

$$P(I) = 1 - e^{-aI}, \tag{3}$$

where I is the Nesterov index, and the value of the parameter a is set to 0.000337. The average number of ignitions during a day is expressed in the form

$$N(PD) = (w(PD)\, PD\, b + l)\, S, \tag{4}$$

where PD is the population density, b=0.1 is the average number of ignitions in a day produced by one human scaled to one million hectares, l is the probability of a fire in some area caused by natural reasons (e.g. lighting), S is the total area of the grid cell in millions of hectares, the function $w(PD)$ describes the human ignition potential

$$w(PD) = 6.8\, PD^{-0.57}. \tag{5}$$

The probability of at least one fire in the area given certain population density PD and Nesterov index I can be expressed in the form:

$$P_1(I,PD) = 1 - (1 - P(I))^{N(PD)}, \tag{6}$$

where probability $P(I)$ and the number of ignitions $N(PD)$ are calculated using the formulas (3) and (4) – (5) respectively.

2.3 Simplifying Assumptions and Constants

We made some assumptions to simplify the assessment of possible forest fires consequences: (a) the whole area under consideration is covered with a homogeneous forest so that the fire conditions in a cell are solely determined by the weather conditions; (b) there are no extreme winds in the area so that we do not account for wind conditions in the model; (c) for the calculations we set the fire spread rate $v = 0.3$ m/min, which is approximately equal to 0.02 km/h. Under the assumption of constant fire spread rate the total area burned during the time t is calculated as the area of the circle of radius vt. We also pose the maximum limit of 24 hours for undetected forest fire assuming that satellite observation system will make it possible to detect the fire within this time frame. In addition we allow 2 hours to extinguish the fire and take this time into account to calculate the burned area.

2.4 Calculation Methodology

In the suggested simplified model the only stochastic variable is the occurrence of fire. The probability of fire occurrence depends on Nesterov index and population density. This rather rough assumption allows us to assess the value of better weather observations in a straightforward way.

Based on the air patrol frequency from the Table A one may estimate the fire detection times and daily patrolled areas depending on the fire danger class. Then the calculation of the total expected FIPI for a full 12x12 cell set can be performed as follows:

$$FIPI = \sum_{i,j=1}^{12}\left(PD_{ij}\sum_{t=1}^{365} S_{ij}^{t}\right),$$

where PD_{ij} is the population density in the grid cell (i,j), and S_{ij}^{t} is the expected relative burned area in the grid cell (i,j) in day t implicitly depending on both Nesterov index and population density. The difference in values of total expected FIPI calculated for ‘rough’ and ‘fine’ grids is due to different fire danger classes assigned to each cell (i,j) on a daily basis using ‘rough’ and ‘fine’ weather data.

3. RESULTS

In order to simulate the usage of coarse weather information, a cell from a fine grid should be selected to represent weather information for each cell of a rough grid. There are several options to choose a ‘small’ cell within an ‘aggregated’ cell. For the illustration purposes we choose the upper left cell. The Table B summarizes the results.

Table B. Total expected FIPI, burned area (% of total area) and cumulative patrolled area (times of the total area) for rough and fine grids and respective improvement ratios

	Rough grid	Fine grid	Improvement
FIPI	0.4496	0.3807	15 %
Burned area	0.5261 %	0.3910 %	26 %
Patrolled area	295.2	300.8	-2 %

Here, we observe the decrease of both total expected FIPI and burned area at the expense of a slight increase in cumulative patrolled area.

3.1 Sensitivity Analysis

We have considered so far just two grid resolutions – ‘rough’ and ‘fine’. The more precise measurement of the sensitivity of the model to the amount of data used to feed it is still of great practical interest. In this section, we adjust the amount of information containing in the input data set by refining the ‘rough’ data set in most critical sub-areas.

We consider a network of weather stations supplying weather data on a ‘rough’ grid, and we increase the number of weather stations in most critical ‘small’ cells. The term *critical* means that the contribution of a particular cell to the total FIPI is maximal among other cells. The FIPI is recalculated for modified (improved) data set and, then, the procedure is repeated to select the next cell where better information should be used. Since we do not specify any further technical details, the suggested approach may, also, be considered as a model of combination of rough and fine data sets representing the integration of two systems, one of which provides relatively rough information at a low cost and the other system supplies relatively costly, but more precise information (this could be e.g. satellite observations and in-situ measurements respectivly).

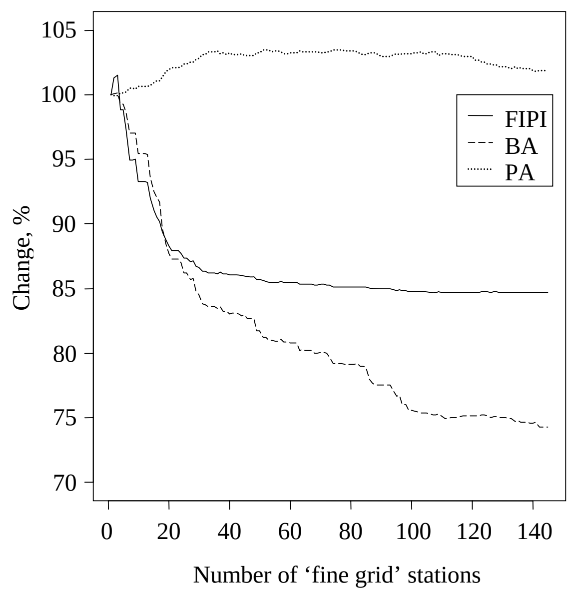

Figure 2. Dependence of the FIPI, burned (BA) and patrolled (PA) areas on the number of ‘added’ weather stations.

Figure 2 illustrates the reduction of FIPI and respective change in burned and patrolled areas depending on the number of added weather stations. The important point to emphasize here is that the introduction of a relatively small number of more precise stations in critical areas could immensely improve the overall performance of the system. So, about 40 precise stations covering only 30% of the territory could provide about 90% of the feasible improvement of FIPI (attainable by placing the weather stations everywhere). At the same time, that still leaves a big potential for improvement in terms of burned area. The optimal combination should take into account the trade-off between the costs for improved information and possible losses caused by fire. Another important implication of the results presented in Figure 2 is the high importance of the model’s performance indicator: if one is just minimizing FIPI they would stop after adding about 40 precise stations (since marginal reduction of FIPI becomes negligible at that point), where those minimizing burned area would still continue improving observation capacity.

Figure 3 shows that the patterns of population density and expected burned areas look quite similar, emphasizing that the population is the main driver of forest fires. At the same time, as we mentioned before in the comment to the Figure 2, the population density alone or even integrated into FIPI cannot be used as the only fire impact measure, since it becomes quite insensitive to burned areas.

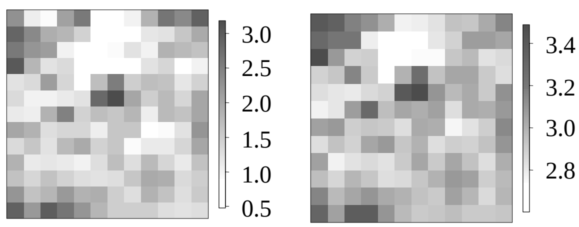

Figure 3. Population density (left figure, inhabitants/km^2) and expected yearly burned areas (right figure, hectares) patterns – both on $\log_{10}$ scale.

4. CONCLUSION

In this paper we analyzed the influence of data quality on the forest fires management model. For the purposes of generality, we did not specify the way the weather parameters are measured. The forest fire detection model presented in this paper is based on the Nesterov fire danger index. The Nesterov index is a natural candidate for simplified fire danger rating, since it is an easily computable function of a few parameters. However, the model can be modified to use similar indices, such as KBDI, see e.g. Buchholz (2000) or more sophisticated systems, e.g. Canadian FFWI, see Van Wagner (1987). The comparison of the sensitivity of different fire danger rating systems to the quality of input weather data with the application to the model presented in this paper could be an interesting direction for further research.

We presented a methodology to assess the benefits of improved weather observations with the application to forest fire management. The results of the modeling could be refined by taking into account other parameters important for forest fire management, such as e.g. fuel load in the forest, type of the forest, age of the forest, resources availability in terms of fire fighters and equipment for fire extinguishing, aircrafts and fuel for forest patrols. We assume that Nesterov index is suitable for the local conditions under consideration. Using more sophisticated systems for the analysis would require much more detailed data, which are usually not freely available. Although the presented analysis is quite basic, we believe that the conclusions will remain valid and that other indices would produce the results in the same direction, although not necessarily to the same extent.

The analysis of the optimal stations' location problem shows that the total system performance can be optimized, and, at the same time, the costs for implementation, operation, and maintenance can be reduced thanks to better overall systems design. A possible interpretation of this result in terms of integration of two systems ('precise-expensive' and 'rough-cheap') leads to the conclusion that an optimal combination of systems (System of Systems) is able to deliver a significant improvement in the overall system's performance as well as improved cost-effectiveness. This conclusion is close to the Global Earth Observation System of Systems concepts, which imply benefits from integration of different observation systems.

REFERENCES

G. Buchholz and D. Weidemann, The use of simple fire danger rating systems as a tool for early warning in forestry, International Forest Fire News, no. 23, pp. 32–36, 2000.

P. Fiorucci, F. Gaetani, R. Minciardi, R. Sacil, and E. Trasforini, Dynamic resource allocation for forest fire risk management, Proceedings of the 15th International Workshop on Database and Expert Systems Applications, pp. 603--607, 2004.

N. Khabarov, E. Moltchanova, M. Obersteiner, Valuing Weather Observation Systems for Forest Fire Management, Systems Journal, IEEE, Volume 2, Issue 3, pp. 349–357, 2008.

V. Nesterov, Forest fires and Methods of fire risk determination, Goslesbumizdat, Moscow, 1949.

S. Saatchi, K. Halligan, D. G. Despain, and R. L. Crabtree, Estimation of forest fuel load from radar remote sensing, IEEE Transactions on Geoscience and Remote Sensing, vol. 45, no. 6, pp. 1726–1740, 2007.

K. Satoh, S. Weiguo, and K. T. Yang, A study of forest fire danger prediction system in Japan, Proceedings of the 15th International Workshop on Database and Expert Systems Applications, pp. 598--602, 2004.

C. E. Van Wagner, Development and structure of the Canadian Forest Fire Weather Index System, Forestry technical report 35, Canadian Forestry Service, Ottawa, 1987.

S. Venevsky, K. Thonicke, S. Sitch, and W. Cramer, Simulating fire regimes in human-dominated ecosystems: Iberian peninsula case study, Global Change Biology, vol. 8, no. 10, pp. 984–998, 2002.

M. Yebra, E. Chuvieco, and D. Riaño, Estimation of live fuel moisture content from MODIS images for fire risk assessment, Agricultural and Forest Meteorology, vol. 148, no. 4, pp. 523–536, 2008.

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The Value of Observations for Earthquake Rapid Response Systems

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Abstract

Every year earthquakes cause substantial economic losses and loss of life in many parts of the world. Earth observation systems may contribute to the efficiency of Rapid Response Measures to avoid or mitigate such losses. However, a quantitative methodology to assess the role of information in such a context has not yet been developed. In this paper we develop a stochastic modelling framework to assess the value of information within a wider range of earthquake rapid response systems. We quantify the benefit of information in terms of cost/rescue efficiency gains depending on the price of observations and rescue resources. When we combine the 'building damage observation system' with the 'building type information system' we find the overall rescue efficiency of the earthquake rapid response system substantially improved. Our results indicate substantial benefits of integrating relevant observation and information systems. These findings will have to be substantiated through real-life case studies.

Key words: Earthquakes, Stochastic analysis, Risk/Benefit analysis, Engineering for hazard mitigation
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1 Introduction

Earthquakes have a great impact on population and economy on a global scale. An earthquake may heavily damage and destroy buildings, bridges and roads, other elements of infrastructure. It can severely injure and kill people. The direct destructive impact of an earthquake may be greatly amplified by induced fires, landslides, tsunamis or epidemics. The US Geological Survey (USGS) lists over 80 significant events [1] defined as 'earthquakes of magnitude 6.5 or greater or ones that caused fatalities, injuries or substantial damage' in the year 2007. The earthquake of magnitude 7.7 on Richter scale that occurred in India on the 26th of January 2001 has caused more than 20 000 fatalities and affected over 6.3 million people. The earthquake of magnitude 7.6 on Richter scale that occurred in Pakistan on the 8th of October 2005 has caused more than 73 000 fatalities. A recent earthquake in China in May 2008 has affected over 45 million people and resulted in significant economic losses. The total number of affected (injured and homeless) people exceeded 5.1 million [2]. Due to these possibly catastrophic consequences of an earthquake it is necessary to be aware of the hazard and be well prepared for it.

The complexity of an earthquake as a geophysical phenomenon and the lack of the humankind's understanding of deep underground processes causing it do not allow to reliably predict earthquakes with current state of technology and science. Nevertheless, the consequences of the disaster may be substantially reduced through proper preparation and rapid response to the event. For example, the large decrease in the average number of deaths resulting from earthquakes in rich countries may in part be attributed to better building and land-use codes and to the improved enforcement of these codes (Tucker, 2004).

This paper focuses exclusively on the intervention phase of the earthquake disaster cycle, namely the rescue operations. We present an analysis of an earthquake rapid response system and the dependence of its efficiency on available information and resources. In particular, we analyze the potential efficiency gains to an earthquake rapid response system due to improved earth observations.

We consider a simple model of an aftermath response, the main purpose of which is to save as many lives as possible immediately after the earthquake. The critical factor to be taken into account when planning a rescue operation in the extreme post-earthquake conditions is the limited time window during which it is still possible to save people caught in the ruins or in urgent need of

[1] According to *http://earthquake.usgs.gov/eqcenter/eqarchives/significant/* accessed on 05 August 2008.

[2] Source for the earthquake statistics is EM-DAT: The OFDA/CRED International Disaster Database, Université catholique de Louvain, Brussels, Belgium.

medical help. This time window for a particular person is not well-defined but strongly depends on the severity of the trauma. The studies on earthquake-caused injuries (see eg. Lee et al. (2005), El Morjani et al. (2007), Lockey (2001), ZEMPINFORM (2001)) state that a severely injured human being may be saved only within a relatively short period of time ranging from 4 hours to 15 minutes. The success of a rescue operation and the number of fatalities is strictly limited by these bounds.

According to the methodology presented in Seligson and Shoaf (2003), the number of severely injured people in a building depends on the damage caused by an earthquake to the building and on the type of the building. For all building types the partial or total collapse of the building dramatically increases the number of severely injured people. Hence, when modeling consequences of an earthquake it is important to explicitly take into account the event of such a collapse. In particular, it may be described in probabilistic terms. Smyth et al. (2004) present assessment of probabilities of a building's collapse for different building types and according to the severity of ground shaking. Application of the probabilistic approach to the damage assessment is reasonable due to uncertainties associated with peculiarities of the building's construction as well as of the local soil conditions, which may lead to amplification or attenuation of the ground shaking induced by an earthquake (see, e.g., Midorikawa et al. (2000)).

Response time is a critical factor for successful post-earthquake rescue operation. We assume that the rescue brigades are to be assigned to specific areas immediately after the disaster. Each brigade continues to work for some time in the assigned area in order to save as many people as possible. If the work is completed, the brigade may, in principle, move on to the next affected area. However, any such relocation takes time and for the purposes of our modeling we assume the mobility to be limited. I.e., the brigades stay in their initially assigned areas independent of the amount of work there. This assumption means that the brigades should ideally be sent to the most affected areas and also allows us to posit a question of optimal resource distribution.

The optimality of the rescue effort distribution may be aided by various observation systems and models, based on them. Therefore, such observations or modeling results may be considered an additional input into the production of a 'safer world'. However, since neither such data nor rescue effort are of unlimited availability and may require investments, choices about the relative proportion of investment into different systems must be made. We consider such choices within the economic analysis framework to discover the properties of optimal system development strategies.

In what follows, we start by describing a simple stochastic model of an earthquake aftermath rescue activity in a city consisting of homogeneous identical blocks and discuss its implications. We then move on to a more complex model with two different types of buildings. Finally, we describe an economic analysis of optimal investment in observation systems and rescue resources. We conclude by discussing the directions of further research.

2 Basic Model

We use stochastic approach to model damages caused by an earthquake to the buildings in a city. To keep the model simple, we omit from the model such infrastructure elements as roads, bridges, power lines, etc. We also ignore the knock-on effects such as fires, tsunamis, landslides and epidemics, focusing primarily on collapsed buildings.

The stochastic model is able to catch the essence of the problem and, at the same time, keep it simple by avoiding the use of excessive amount of technical information such as physical properties of buildings, soils, and spectral characteristics of ground motion. The probability of collapse is a commonly used characteristic describing the response of engineering structures to a strong ground motion (see e.g. Smyth et al. (2004)) and therefore is a proxy for stochastic modeling of an earthquake-caused damage. Collapsed buildings can be detected by analyzing pre-event and post-event high-resolution satellite imagery provided by e.g. IKONOS and QuickBird satellites (see Yamazaki (2005)). These considerations make the model's structure and assumptions reasonable and relevant to applications.

We divide the city into a set of N blocks, containing n houses each. We assume, for the simplification, that in case of an earthquake each house has the same probability of collapse p. We further assume that in case of a collapse, v people in the building will be in need of a rescue, so that the number of victims in the i^{th} block is $v\xi_i$, where $\xi_i \sim \text{Bin}(n, p)$. In other words, in the aftermath of an earthquake, each house in our city is in one of the two possible states: collapsed/damaged with v victims or intact with 0 victims.

Assume, that each rescue brigade is able to save at most v victims (i.e., all the inhabitants of a single collapsed house). Then the total number of rescue brigades, the *rescue effort*, necessary to save all the victims in the city (provided perfect information is available on the location of collapsed buildings) is equal to the total number of collapsed buildings in the N blocks: $\sum_{i=1}^{N} \xi_i$.

Let X_i denote the number of rescue brigades sent to the i^{th} block. The total number of victims saved in the i^{th} block is then $\min(v\xi_i, vX_i)$ or, equivalently,

$$v\eta_i, \text{ where } \eta_i = \min(\xi_i, X_i). \tag{1}$$

Here, η_i is the number of collapsed houses in block i, the inhabitants of which were saved by the rescue brigades. The quantity of interest to us is the ratio of saved victims to the total number of victims, *the overall rescue efficiency in the city*:

$$\theta = \begin{cases} \frac{\sum_{i=1}^{N} \eta_i}{\sum_{i=1}^{N} \xi_i}, \ \sum_{i=1}^{N} \xi_i > 0, \\ \qquad 1, \ \sum_{i=1}^{N} \xi_i = 0. \end{cases} \tag{2}$$

Note, that the number of victims per building appears both in the numerator and in the denominator, and therefore cancels out and is omitted from further discussion. For the technical convenience, in case of no victims, we assign the rescue efficiency the value of one.

Thus defined, the rescue efficiency θ is a function of a random variable vector $\boldsymbol{\xi} = \{\xi_1, ..., \xi_N\}$ and a number of parameters, such as p and $\mathbf{X} = \{X_1, ..., X_N\}$. It therefore is itself a random variable, characterized by a probability distribution, which in turn can be summarized by, for example, measures of central tendency such as expected value and variance, as well as by measures of range such as quantiles. However, the analytical evaluation of these quantities is impossible in all but a few special cases, and, therefore, simulation studies are required.

To introduce *observations* into the model we assume that in the virtual city of our consideration a rapid post-earthquake damage assessment system is implemented, which allows for the immediate evaluation of the number and location of the collapsed (or heavily damaged) buildings. Such a system may be based on a seismograph network providing input information to the physical model of buildings and soils (see e.g. Midorikawa et al. (2000), Naeim et al. (2005)). A rapid post-earthquake damage assessment system may also rely on building damage detectors, or space-based high resolution imagery Adams et al. (2005). We assume, that out of N blocks only $0 \leq N_o \leq N$ are observed and, correspondingly, N_u are unobserved, so that $N_o + N_u = N$.

We denote the total number of available resources by X^* so that for all possible resource distributions $\{X_i\}$, the following equality holds: $\sum_{i=1}^{N} X_i = X^*$. The resource distribution in the model is based on the observed (or assessed) damage. First, the maximum possible amount X_o^* of resources is allocated to the blocks, where the extent of the damage is known, i.e., to the N_o observed blocks:

$$X_o^* = \min\left(\sum_{i=1}^{N_o} \xi_i, X^*\right). \tag{3}$$

Since we consider the blocks to be interchangeable an optimal distribution of resources among observed blocks is:

$$X_1 = \min(\xi_1, X^*), X_2 = \min(\xi_2, X^* - X_1), \ldots, X_{N_o} = \min(\xi_{N_o}, X^* - \sum_{i=1}^{N_o-1} X_i) \tag{4}$$

The amount X^* cannot, by definition, exceed the total amount of available resources X^*. In the above, without the loss of generality we assume that the observed blocks are numbered $1, 2, \ldots, N_o$. The rest of the available resources, $X^* - X_o^*$, is equally distributed between the non-observed blocks (where the extent of the damage is not known). We assume, that a rescue brigade is indivisible and hence allocate an integer number of brigades starting from the first unobserved block. The amount of resources X_i assigned to the unobserved block i, $i > N_o$ can be expressed as

$$X_i = \alpha + \beta_i, \qquad i = N_o + 1, \ldots, N, \tag{5}$$

where the term

$$\alpha = \left\lfloor \frac{X^* - X_o^*}{N_u} \right\rfloor \tag{6}$$

takes care about the uniform integer distribution between the unobserved blocks, and the term β_i takes care about the full distribution of the rest of available resources between the unobserved blocks:

$$\beta_i = \begin{cases} 1, & N_o + 1 \leq i \leq N_o + 1 + \tilde{N} \\ 0, & N_o + 1 + \tilde{N} < i \leq N \end{cases}, \tag{7}$$

where $\tilde{N} = X^* - X_o^* - N_u\alpha$ is the number of unobserved blocks that get an additional rescue brigade due to the integer distribution of resources. Here, without the loss of generality, we assume the priority distribution of indivisible amount of available rescue resources between the first $\tilde{N}$ unobserved blocks. For further considerations we denote by q the observation quality - the ratio between the observed N_o and the total number of blocks N in the city

$$q = \frac{N_o}{N}. \tag{8}$$

Assuming that all the X_o^* brigades are assigned correctly and operate efficiently, the following equality holds:

$$\sum_{i=1}^{N_o} \eta_i = X_o^*.$$

This, applied together with 1, 4 and 5 for $i > N_o$ allows to calculate the efficiency according to 2 for each simulated damage distribution. In what follows we will use the normalized value to describe the total available amount of resources:

$$x = \frac{X^*}{Nn}.$$

If $x \geq 1$, then the amount of available rescue resources is sufficient for all the possible damages all the victims in need of help could be rescued.

3 Non-homogeneous Model

In order to model the integration of relevant information systems and to analyze the benefits of such integration - the *System of Systems* (SoS) effect - we have modified the model to represent a non-homogeneous area, which is, of course, more realistic than the homogeneous assumption. In addition to the damage observation subsystem, already described above, we introduce a building inventory subsystem, which provides valuable information about building types. A building inventory is a structure-specific database, which may include square footage, building age and condition, occupancy status, utilization rate etc. For our purposes we only need two basic characteristics: the ability of a building to withstand an earthquake and the number of residents. For each building of type $j = 1, 2, \ldots, J$ we represent this information as a pair of parameters

$$(p_j, v_j), \tag{9}$$

where p_j is the probability of collapse and v_j is the number of victims in case of collapse of the building of type j. We assume, that all the buildings within a single block are of the same type, and that one unit of rescue effort is required to save one unit of victims. Assuming N_j blocks of type j, the rescue effort sufficient to help all the victims of a completely collapsed virtual city equals to $X^* = \sum_{j=1}^{J} v_j N_j$. Note, that for a situation with $J = 2$ types only, the calculation of efficiency according to Equation 2 knowing the ratio $\frac{v_2}{v_1}$ is sufficient.

The quality of the input data for the rapid earthquake response system can be described by the pair (q, d), where q is as described in Equation 8 and d indicates the extent of building inventory information available. For the sake of simplicity, here we consider only binary values for this parameter:

$$d = \begin{cases} 1, & \text{if the inventory is available,} \\ 0, & \text{if the inventory is not available.} \end{cases}$$

We analyze the impact of possible combinations of the two subsystems on the overall efficiency of the post-earthquake rapid response system, i.e., in each of the following cases: when neither the damage observations nor the building inventory are available, when either one of the two are available, and, finally, when both subsystems are functioning together. In each of the above cases the system's performance is measured against the same resource limitation assuming optimal distribution of rescue effort under different amounts of information available. In the end the results are compared to quantify the benefits of using separate subsystems and their combination.

4 Simulations

For the purposes of simulation runs we model a small homogeneous city consisting of $N = 100$ blocks, $n = 10$ houses each. For a fixed combination (p, q) we simulate 10000 times the damages inflicted by an earthquakes on the buildings of the virtual city. In each simulation, we sample the number of collapsed buildings in each of N blocks from a binomial distribution with parameters (n, p). We then simulate the resource distribution according to the Equations 3 and 5, and finally evaluate the resulting efficiency according to the Equation 2.

The results of the simulations for different combinations of resource limitation x and probability of collapse p are summarized in Figure 1 for the two extreme cases where there is no information about the earthquake-caused damage and where there is complete information on the damage incurred. The right-hand panel representing the latter case demonstrates how the system's performance suffers from the lack of resources, when despite the full information on the location of the damaged buildings there is no possibility to provide necessary resources in the timely fashion. The left-hand panel reflects the case where there is no information available on the damaged buildings. Evidently, the lack of information could be compensated for by having more resources available than is necessary for the perfect information scenario (the same efficiency is achieved for the larger amount of resources).

Figure 2 shows how the assessment of efficiency $\tilde{\theta}$ (here at the 95% confidence level) and mean efficiency $\bar{\theta}$ can be improved by better observation quality for different values of resource limitation x. Evidently, the observation system is very important in case of insufficient amount of rescue resources. Relative gain in the rescue efficiency for $x \in (0, .12)$ is within the range of $60 - 70\%$. As the amount of resources x increases over the amount necessary to save the expected number of victims under the full info scenario, the relative gain of the θ Earth Observations (E.O.) falls down to 10%. The lack of rescue resources is usually the case especially for large catastrophic earthquake events, where the importance of E.O. becomes evident.

For the implementation of a non-homogeneous model, we simulate a city with two types of buildings, characterized, according to the notation of Equation 9 by the following parameters:

$$p_1 = .10, v_1 = 1, p_2 = .05, v_2 = 3.$$

I.e., the first type is twice as prone to collapse as the other one, but suffers thrice as few victims as a result of collapse. We assume that the city blocks are divided equally between these two types: $N_1 = N_2 = 50$.

We have performed simulations for the pairs (q, d) such that $q, d \in \{0, 1\}$ and for different values of resource limitation x. Figures 3 and 4 demonstrate the simulation results. The usefulness of building inventory is clearly evident in both the extreme cases $q = 0$ and $q = 1$. Comparing Figure 3 to Figure 4 one may conclude that implementing only one of the two subsystems (top line in Figure 3 and bottom line in Figure 4) delivers less efficiency than both subsystems together (top line in Figure 4, which is an obvious benefit from using two coordinated subsystems together - a System of Systems effect.

5 Optimal Rescue Resource Distribution.

An optimal rescue resource distribution strategy depends on the values of q and d, which are the informational characteristics of the system. Below we give some comments on the resource distribution approaches implemented in the model for different combinations of binary values of q and d.

In case of $q = 0$ and $d = 0$, representing the situation where no information is available on either damage or building stock, the resource distribution is made according to the detailed description in Equations 3 and 5 with only a minor modification. The resources are distributed uniformly among all the blocks according to Equation 6, and the rest of the resources which cannot be integrally divided between the blocks is distributed uniformly between the different types of blocks in a manner, similar to that described in Equation 7. First, a rescue unit is assigned to a block of 'type 1', the next rescue unit is assigned to a block of 'type 2', the following unit is assigned to a block of 'type 1' again, and so on until the resources run out. This approach takes into account the existence of the two types of blocks and relies on the ability to distinguish between them. Yet it does not use any information on the actual characteristics (p, v) of the buildings. Random selecting of blocks without regard for the existence of two types of blocks would deliver similar results in our setting because of the equal amount of 'type 1' and 'type 2' blocks in the selection.

Case $q = 1$ and $d = 0$ means that we know perfectly the extent and location of the damage, but we do not know the type of the damaged buildings, i.e., the amount of injured in need of a rescue there. In this case the resources are distributed exactly as in the previous case with the following modifications: (1) the set of blocks should be limited to the ones with the reported damage and (2) each additional resource we might have available after the initial uniform distribution should only be sent to the block i if the amount of resources X_i already assigned to it is less than the maximum possible amount of victims within the block, i.e $X_i < \xi_i \max(v_1, v_2)$. Meeting this condition guarantees that the rescue resources are not wasted on the blocks, which are already allocated enough resources to save every inhabitant a priori.

In case $q = 0$ and $d = 1$, that is if we know all the building types, but do not know the locations of the collapsed buildings, the available resources are distributed stepwise in the following manner. For each step, a unit of available resources is distributed to that block i' where the probability P of rescuing people is the highest, taking into account the amount of resources X_i already sent out, i.e, $P(i', X_{i'} + 1) \geq P(i, X_i + 1), i = 1, \ldots, N$.

In case $q = 1$ and $d = 1$ when both the subsystems are supplying information to the earthquake rapid response system, the resource distribution is trivial - we simply send the necessary amount to the damaged buildings in accordance with the building type. For each collapsed 'type 1' building we send v_1 units of rescue resources and for each collapsed building of 'type 2' we send v_2 units as long as we have enough rescue resources available.

6 Cost-Benefit Considerations

We will now consider the problem of optimal investment in the earthquake rapid response system. We are interested in the proportion of investments into surveillance vs. investment into formation and maintenance of the rescue force such that the utility is maximized for a certain amount of total investment or, alternatively, such that the total investment is minimized for a given level of utility. For the purposes of this analysis we assume the utility function to be equal to the expected rescue efficiency. An iso-utility curve, then, represents all combinations of inputs, in our case, the rescue resource availability x and observation quality q, resulting in the same utility, i.e., expected rescue efficiency. In Figure 5 we have plotted the simulated iso-utility lines, corresponding to difference levels of efficiency achieved with at least 95% probability for $p = .3$. Assuming the relative price of surveillance compared to that of rescue effort to stay constant, the straight lines correspond to iso-cost lines at different levels of total expenditure. The optimal distribution of resources, given a certain expenditure level, is reached at the point where the corresponding iso-cost line is tangent to the highest possible iso-utility curve. Some such optimal points are marked in the Figure 5 by large dots. The general tendency appears to be such, that with the increased availability of financial resources, both the surveillance and the rescue effort spending will be increased to achieve the highest efficiency. Nevertheless, when the finances are sufficiently low (left-most iso-cost curve) or the relative price of surveillance is sufficiently high (dotted line), only the rescue effort will be obtained. This is reasonable, since, although it is natural to obtain non-zero rescue efficiency without any surveillance, the rescue efficiency without any rescue effort is always zero, no matter how good the surveillance is. An important result of the model is that with the increasing requirements for efficiency (safety) the portion of E.O. in the optimal investment strategy grows more sharply than the resources part (convex dotted curve).

7 Discussion

In the model presented above, we have demonstrated basic properties of the interplay between the extent of surveillance, rescue effort availability and distribution, and the resulting rescue efficiency in the aftermath of an earthquake described by the number of victims dependent on the varying probability of a structural collapse. We have also briefly examined economic issues associated with the resource availability and cost of information We conclude that the overall system efficiency can be improved not only by incorporating more information but also through integration of various information subsystems.

The model presented here is intentionally simplistic in that it does not include several important factors that may have substantial impact on rescue efficiency. It considers the victims of an earthquake-caused building collapse seperately from the other consequential disasters such as fires, landslides, epidemics, possible chemical contamination, etc. We also assume a constant probability of collapse p and a constant number of victims per collapsed building v. In order to improve on this assumptions spatially explicit data on inter alia soil properties and and engineering properties of the buildings would be needed to inform these parameters The number of victims also depends on the time of an earthquake occurrence and on the social aspect of the building (offices are full by day and generally empty by night). The model does not account for accessibility problems caused by the infrastructure damages, which might make the desired rescue effort distribution unobtainable. These are certainly aspects to be incorporated in further research. Nevertheless, although stylized, the model presented here does provide important insights into basic workings of the studied phenomenon.

We have investigated the effect of p and v to some extent by considering a mixture of two different types of buildings. One might argue that if the precise information regarding the local soil conditions (micro zonation) and therefore a realistic shaking map as well as building-specific information are available, one might include more types, producing a continuous spatial field of (p, v)-characteristic. Still, no matter how much information is taken into account with the current level of knowledge, both, the probability of collapse and the resulting number of victims, also have a random component. The parameters p and v may then themselves be assigned probability distributions, for example, Beta and Poisson respectively. In our case, however, due to the absence of information, this would require too many assumptions and would therefore obfuscate rather than clarify the matter. Although the presented model provides solution for the fixed values of (p, v), it can easily be extended to any deterministic or random field of this parameter pair. A further step would be to dispense with the binary hierarchy of collapse vs. no collapse and the ensuing victim count and to consider the latter a single continuous variable. However, choosing a probability distribution in this case is problematic. For example, the incorporation of the information on soil, engineering and social aspects, mentioned above into the two parameters of a naturally suitable Gamma distribution is a major challenge.

The analysis assumed fixed block size i.e. number of buildings per block ($n = 10$). This parameter mimics the degree of mobility of rescue brigades. If the the entire city were assumed to consist of one block, this would mean that rescue brigades can freely move to any part of the city and that they would perfectly solve the optimal rescue resource distribution problem achieving average efficiency of $\frac{X^*}{np}$ for large enough n.

Subsystems other, than already mentioned, may substantially contribute to the overall system's performance. Security monitoring within buildings and transport flow models dealing with the spatiotemporal distribution of the city inhabitants may provide valuable information input. The importance of these data to evaluating the most critical locations, the fastest access routes and thus the most efficient rescue effort distribution is unquestioned, yet the efficient use of this information is a matter of proper integration of the existing systems.

The economic analysis in this study considered the choice between investing in surveillance (passive observation) and investing in rescue effort (active participation). The resulting cost and utility curves may be considered as an aid either in a utility maximization problem (obtaining maximum rescue efficiency with probability of at least 95% conditional on the fixed expenditure) or in an expenditure minimization problem (obtaining desired rescue efficiency with probability of at least 95% with the minimum possible cost). More subsystems should be incorporated as described above, so that this analysis may be extended to account for multiple inputs.

In conclusion, the model presented here, although simplified, provides useful insights in the rescue effort optimization and the value of observations and integration of information systems within the framework of the rapid earthquake response. It also provides a good base for further research, which should incorporate a more detailed treatment of the damages distribution and an integration of multiple information subsystems.

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References

Adams, B., Mansouri, B., and Huyck, C. 2005. Streamlining post-earthquake data collection and damage assessment for the 2003 Bam, Iran, earthquake using VIEWS^{TM} (Visualising Impacts of Earthquakes With Satellites). Earthquake Spectra 21:S1, S213–S218.

El Morjani, Z., Ebener, S., Boos, J., Ghaffar, E., and Musani, A. 2007. Modelling the spatial distribution of five natural hazards in the context of the WHO/EMRO Atlas of Disaster Risk as a step towards the reduction of the health impact related to disasters. International Journal of Health Geographics, 6:8.

Lee, V.J., Low, E., Ng, Y.Y. and Teo, C. 2005. Disaster relief and initial response to the earthquake and tsunami in Meulaboh, Indonesia. Annals Academy of Medicine, Singapore, 34:9, 586–590.

Lockey, D.J. 2001. Prehospital trauma management. Resuscitation 48, 515.

Midorikawa, S., and Abe, S. 2000. Real-time assessment of earthquake disaster in Yokohama based on dense strong-motion network. 12WCEE, Paper 1036.

Naeim, F., Hagie, S., and Alimorandi, A. Automated post-earthquake damage assessment and safety evaluation of instrumental buildings, SMIP05 Seminar on Utilization of Strong-Motion Data, pp. 71-88.

Seligson, H.A., and Shoaf, K.I. 2003. Human impacts of earthquakes. in W. Chen, and C. Scawthorn, (Editors). Earthquake engineering handbook. CRC Press, p. 28-13.

Smyth, A., Altay, G., Deodatis, G., Erdik, M., Franco, G., Gülkan, P., Kunreuther, H., Lus, H., Mete, E., Seeber, N., and Yüzügüllü, Ö. 2004. Probabilistic benefit-cost analysis for earthquake damage mitigation: evaluating measures for apartment houses in Turkey. Earthquake Spectra, 20:1, 171–203, 2004.

Tucker, B. 2004. Trends in global urban earthquake risk: a call to the international earth science and earthquake engineering communities. Seismological Research Letters, 75:6, 695–700.

ZEMPINFORM No. 4 (46), July-August 2001, Government of Moscow, Health Committee, Scientific–Practical Center of Emergency Medical Help, Russia (in Russian).

Yamazaki, F., Yano, Y., and Matsuoka, M. 2005. Damage detection in earthquake disasters using high-resolution satellite images, Proceedings ICOSSAR, Safety and Reliability of Engineering Systems and Structures, Millpress, Rotterdam, ISBN 90 5966040 4, pp. 1693–1700.

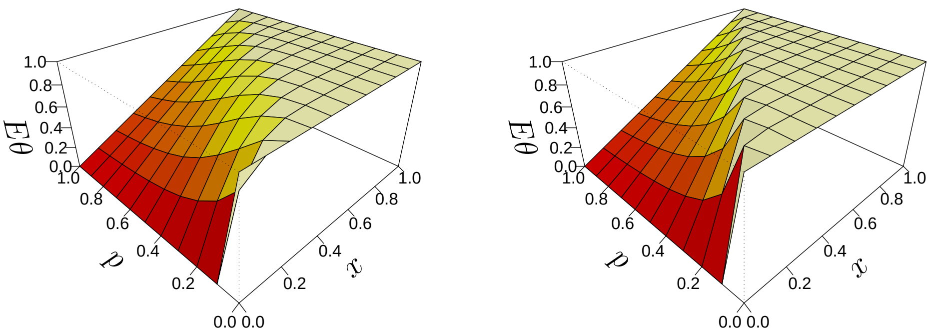

Fig. 1. Expected efficiency $E\theta$ depending on the probability of collapse p and resources limitation x for no observations (left graph) and with observations (right graph).

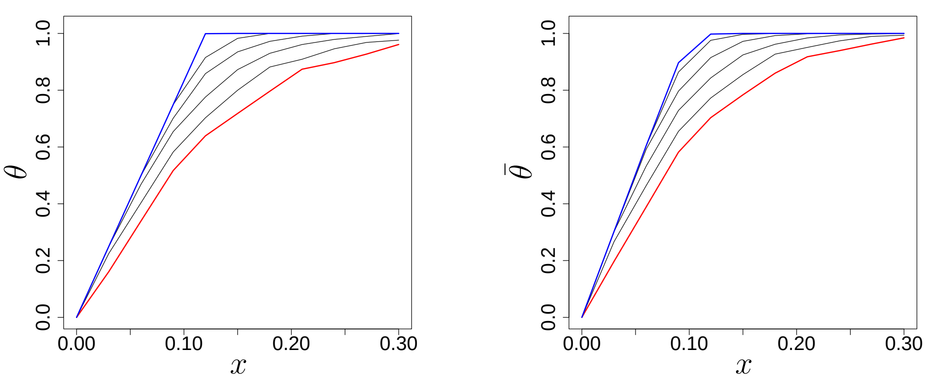

Fig. 2. Efficiency at 95% confidence level ($\tilde{\theta}$, left graph) and mean efficiency($\bar{\theta}$, right graph) depending on resources x for different observation quality (bottom line corresponds to $q = 0$, upper line corresponds to $q = 1$). Probability of collapse $p = 0.1$.

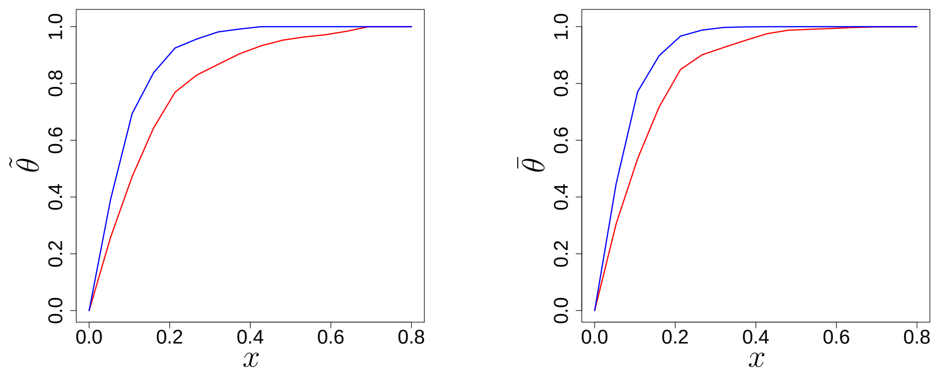

Fig. 3. Efficiency at 95% confidence level ($\tilde{\theta}$, left graph) and mean efficiency ($\bar{\theta}$, right graph) depending on resources x for observation quality $q = 0$ with and without using building inventory information d (bottom line represents $d = 0$, upper line represents $d = 1$). Probability of collapse $p = 0.1$.

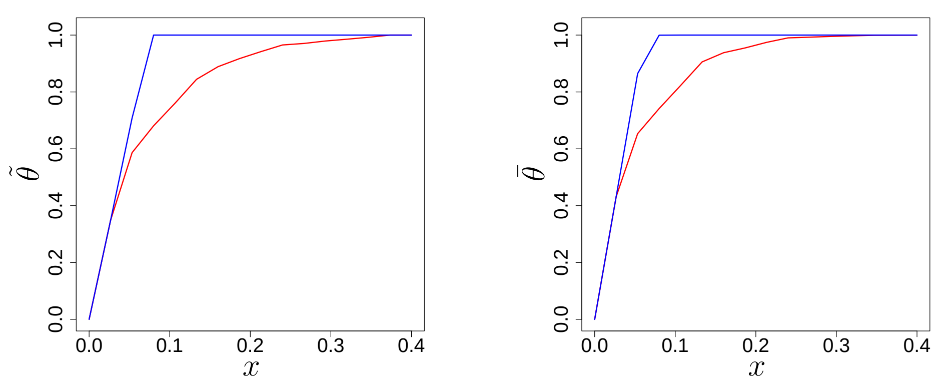

Fig. 4. Efficiency at 95% confidence level ($\tilde{\theta}$, left graph) and mean efficiency ($\bar{\theta}$, right graph) depending on resources x for observation quality $q = 1$ with and without using building inventory information d (bottom line represents d, upper line represents $d = 1$). Probability of collapse $p = 0.1$.

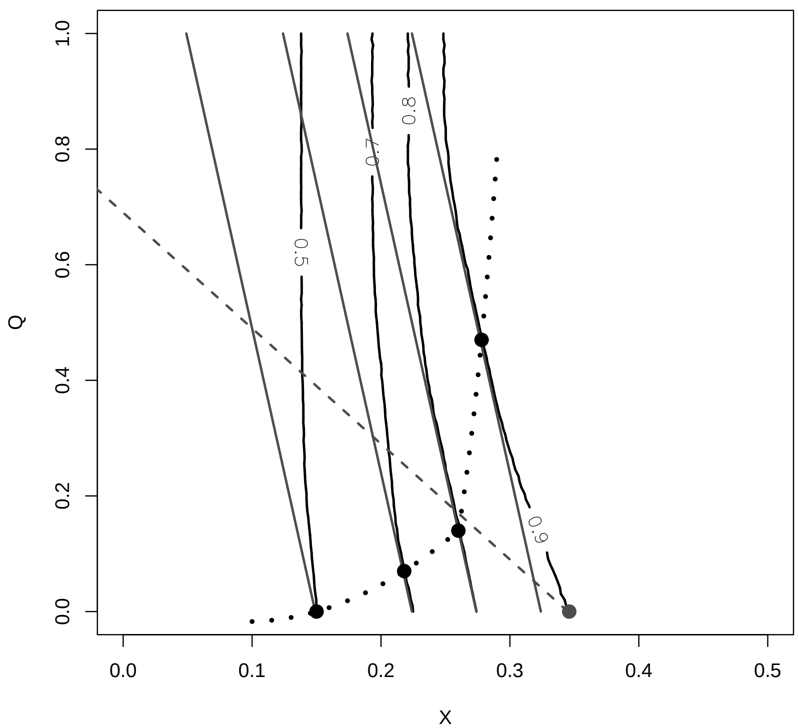

Fig. 5. Economic analysis of the optimal resource distribution. The points of tangency of iso-cost lines (black) to iso-utility lines (gray) represent optimal choices for a given expense level and relative costs of surveillance and rescue resources.

A Markov chain model for observation dependent disaster risk decision making

P. Brunovský I. Melicherčík

1 Introduction

This short note represents an attempt to formalize mathematically the process of observation depending decision making under uncertainty. To use it in practice one needs to determine the transition probabilites of the Markov chain of the model. This requires a knowledge of the transition matrix defining the chain. which has to be computed from from past statistical data.
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2 The model

Let us characterize the environment by a finite number of "states of nature" labeled by natural numbers $1 \ldots, N$ the label N being reserved for "disaster". The states may represent intervals of the values of temperature, precipitation, wind, water level or vectors of their combinations. We follow the values of those variables in equidistant time instants and assume that their time development is governed by a homogeneous Markov chain defined by the $N \times N$ matrix of transition probabilities

$$P = (p_{ij})_{i,j=1\ldots N},$$

where p_{ij} is the conditional probability of the nature being in state j at time $t+1$ under the condition that it was in state i at time t.

Further, we make the following assumptions:

- In case nature reaches the disaster state N at some time t, the community suffers a loss of magnitude D_0

- The community can take measure to prevent the disaster losses; in case it does, the magnitude of losses is D_1, while the cost of preparation has magnitude A, where $A + D_1 << D_0$

The strategy of the community is to take measures to prevent losses in case it is in a state in which the conditional probability of reaching the disaster state at the next period exceeds a certain threshold b. Then, the average conditional loss L_i under the condition that the state of nature is i is given by

$$L_i = \begin{cases} p_{iN} D_0 & \text{if } p_{iN} < b \\ p_{iN}(A + D_1) + (1 - p_{iN})A & \text{if } p_{iN} \geq b \end{cases}$$

Assume now that the Markov chain given by P has a unique stationary probability vector $\pi = (\pi_1, \ldots, \pi_N)$ (a sufficient condition is that for some k all entries of P^k are positive). Under these conditions the long-term average loss is

$$L = \sum_{i=1}^{N} \pi_i L_i$$

A basic problem now is to determine b in order to minimize L.
Further comments:

- The Markov chain can be generated in various ways, e. g. by a process with independent increments (e. g. a reservoir is being filled, the disaster being overflow, state are then intervals of level heights)

- Other possible optimization problem: refinement of the intervals defining states of nature, in this case the cost of additional observation should be included into the objective function.

3 A modified model

A modified model could be used to supplement the model of fighting forest fires proposed by Khabarov ([Kh2007]).

There are $m + 1$ posibilities of preparing for the disaster with different costs $A_0, A_1, \ldots A_m$ where $A_0 = 0$ means no preparation. In the case of [Kh2007] the different preparations could be seen in table on page 7, the costs could be found in equation (6). The different kinds of preparation correspond to different frequencies of patrols. Each kind of preparation implies different costs $D_0, D_1, \ldots D_m$ in the case of the disaster. The corresponding costs in [Kh2007] are in the table on page 6 and in equation (6). The objective is to assign to each state i the kind of preparation $j(i)$ to minimize the total average loss. The average conditional loss L_i under the condition that the state of nature is i is given by

$$L_i = A_{j(i)} + p_{iN} D_{j(i)} \,.$$

The total average loss is then given by

$$L = \sum_{i=1}^{N} \pi_i L_i$$

where π_i is the probability of the state i. In the case of [Kh2007] this probability is proportional to the surface of the area with corresponding state. The objective is to minimize L with respect to different functions $j(i)$.

4 References

[Kh2007] Nikolay Khabarov, Elena Moltchanova: Impact of Weather Observations on Efficiency of Fighting Forest Fires, publication of the GEO-BENE project

III.6. SBA ECOSYSTEMS by GEO-BENE Consortium Partners

The role of GEOSS in monitoring ecosystems and their services

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Abstract

Global declines in biodiversity and ecosystem services have triggered national and international agreements to halt and reverse these trends (e.g. the Convention on Biological Diversity's target of achieving a significant reduction in the current rate of biodiversity loss by 2010). These agreements have highlighted the need for monitoring systems which accurately describe the conditions and trends of biodiversity and ecosystem services, as well as the drivers of change. GEOSS aims to contribute to these needs in the ecosystems and biodiversity benefit areas. We demonstrate the benefits of GEOSS in the monitoring and assessment of biodiversity and ecosystem services using a case study from a semi-arid biodiversity hotspot in South Africa. Using data poor (non-GEOSS) and data rich (GEOSS) scenarios we highlight the substantial differences found in biodiversity and ecosystem service condition. We link these findings to the need for careful and well informed management of ecosystems in semi-arid regions. We conclude with a summary of the costs and benefits of improved data.

Keywords: Biodiversity, indicators, degradation, overgrazing, cost-benefit

1. INTRODUCTION

Global declines in biodiversity have been more rapid in the past 50 years than at any other time in human history with indications that losses will to continue well into the future with little indication of changes in the drivers that cause them (MA, 2005). These declines are concerning, not just because they represent a substantial loss of life and diversity on earth, but also because they threaten our basic life support systems. Biodiversity makes up these life support systems which provide many benefits (or ecosystem services) to humans. These services include provisioning (e.g. food and timber), regulating (e.g. clean air and water), and cultural (e.g. tourism and spiritual values) services which are important to many components of human well-being, including security, basic material for a good life, health, good social relations, and freedom of choice and action (MA 2005). The Millennium Ecosystem Assessment demonstrated that, in a similar way to biodiversity, most ecosystem services are in a degraded and declining state and will substantially diminish the benefits that future generations obtain from ecosystems, representing a significant barrier to achieving the Millennium Development Goals (MA 2005).

An awareness of these declines, as well as an increasing appreciation of the negative impacts they will have on human wellbeing, have led to a number of national and international agreements and conventions aimed at stopping this degradation of biodiversity and ecosystem services. The Convention of Biological Diversity's target to achieve a significant reduction in the current rate of biodiversity loss by 2010 (UNEP, 2002) is an example of such an agreement. These agreements have highlighted the need for good monitoring systems; and simple and practical indicators to measure progress towards these targets (Reyers *et al*. 2007). At the same time they have pointed to the inadequate data and knowledge currently available with which to populate these indicators and monitoring programs (MA 2005). The absence of well-documented, comparable, time-series information for many components of ecosystems poses significant barriers to the measurement of the condition and trends in ecosystems and their services.

The Global Earth Observation System of Systems (GEOSS), in its 10 year implementation plan, takes note of these needs for improved ecosystem monitoring and aims to provide improved observations of ecosystems for decision-makers in the field of natural resource management at the global, regional and national levels (GEO 2005). It focuses on methods and products of ecosystem extent and ecosystem condition with an ultimate aim of enabling: "the production of spatially-resolved information on ecosystem change, condition and trend, in relation to their capacity to deliver sustainable ecosystem services in sufficient quantities to meet societal needs; i.e. maps of ecosystem health, risk and vulnerability with sufficient resolution to support national and global decision-making".

This study, as part of the EC funded GEOBENE project, aims to assess the benefits of such improvements in earth observation, specifically within the Societal Benefit Areas of biodiversity and ecosystems. It does so using a case study from South Africa where high quality earth observation products are used to assess the condition and trends in ecosystem services. These high quality products are similar to those outlined by the GEOSS 10 year plan. These results are then compared to an assessment of ecosystem services using lower quality earth observation products (a non GEOSS scenario). This comparison allows for the quantification of the benefits of improved earth observation data.

2. METHODS

The study is based in the Little Karoo of South Africa (~19 000 km^2); a semi-arid, intermontane basin, where vegetation associated with three globally-recognized biodiversity hotspots intersects and intermingles. Rainfall varies from < 200 mm to > 1200 mm and high levels of solar radiation (>80%) result in potential evapotranspiration of > 10 times the rainfall (2250 mm/yr). The major form of land-use has, since the 1730s, been extensive grazing and browsing by livestock, chiefly ostriches, but also sheep and goats. Historical records indicate certain districts in this region have been heavily overstocked by cattle, horses, donkeys, sheep, goats and ostriches, leaving large areas of degraded vegetation and soil (Dean & Milton 2003; Cupido 2005).

The area has been the site of a long term research project on ecosystem services and biodiversity and as a result has several high quality databases on biodiversity, ecosystem services and

The IIASA-coordinated EC project GEO-BENE provided financial support.

land cover. Of particular relevance is a database on the spatial extent of land transformation and degradation of the Little Karoo mapped at a 1:50 000 scale (Thompson *et al*. In Press). This map depicts areas of pristine vegetation and transformed (cultivated and urban) areas, but importantly it also maps moderately and severely degraded areas. Moderately degraded areas are those where although the plant communities have been impacted by grazing, this impact is limited mostly to the trampling and degradation of biotic crusts, some soil loss and declines in the populations of palatable species. Severely degraded areas have been substantially overgrazed and have no biological soil crusts, severe soil loss and totally altered plant communities (complete loss of palatable species). Land degradation was quantified using a novel technique, based on intra-annual variance in NDVI values, calibrated for different vegetation units mapped at 1: 50 000 scale, and ground truthed via expert assessment (Thompson *et al*., In Press).

These land cover data, as well as spatially explicit data on biodiversity and the ecosystem services of forage for livestock grazing, water flow regulation, carbon storage, erosion control and tourism were collated. Using data extracted from (Rouget *et al*. 2006; Reyers *et al*. In Press) on the ecosystem specific impacts of land cover on biodiversity and each ecosystem service, the study quantified changes in biodiversity and ecosystem services as a result of land cover change in the Little Karoo. As the land cover data were only available for 2005, our analyses are based on the difference between the 2005 data and the pre-colonial condition where all areas are assumed to be pristine (as per Scholes and Biggs 2005). This assessment represents what would be possible if GEOSS were in place and is termed the "GEOSS scenario".

We then repeated the above methods, but this time using land cover data available at a national scale. These data, suitable for 1:50 000 scale applications, were derived from seasonal (two seasons satellite imagery), ortho-rectified, standardised, high resolution digital satellite imagery from Landsat 7 Enhanced Thematic Mapper (ETM+), which were acquired principally during 2000 – 2002. No ground truthing, post processing or expert assessment was performed on these data. This assessment of ecosystem service and biodiversity condition was chosen to represent the "non-GEOSS scenario".

3. RESULTS

The results of the GEOSS scenario assessment indicate that the Little Karoo's is currently comprised of 38% natural vegetation cover with another 10% cultivated or urban areas; the remainder is made up of moderately (37%) and severely (14%) degraded areas (Figure 1). The non GEOSS scenario shows the Little Karoo has 93.6% of its areas still covered with natural vegetation and only 5.8% in cultivated or urban areas; the remainder of 0.7% is classified as degraded (with no distinction between severe or moderate levels of degradation).

This large discrepancy in land cover composition has implications for the assessment of biodiversity and ecosystem service condition. An indicator of biodiversity condition called the Biodiversity Intactness Index (BII), provides a score of 65.4% for the GEOSS scenario, while the non GEOSS provides a score of 86.5% (Rouget *et al*. 2006). The Biodiversity Intactness Index is a measure of the average population size (abundance) of all well-described taxa, relative to their reference populations in a particular ecosystem type (nominally those of the pre-colonial period; Scholes and Biggs 2005).

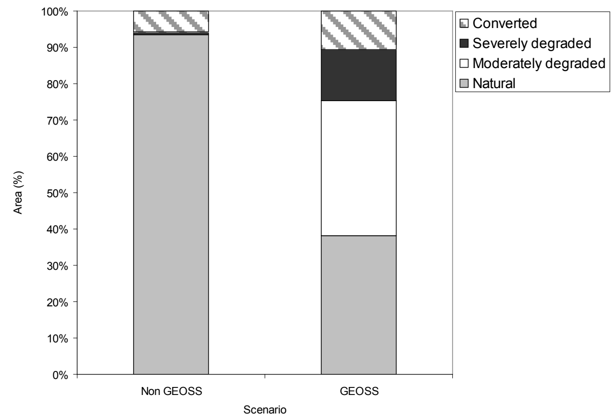

Figure 1: Land cover categories and percentage coverage based on GEOSS and non GEOSS scenario databases for the Little Karoo of South Africa.

These changes in biodiversity condition, as well as the assessed changes in ecosystem services are reflected in Figure 2. The changes are represented as proportions of the potential supply of the ecosystem service for both GEOSS and non GEOSS scenarios. When compared to potential service supply, the GEOSS scenario demonstrates that erosion control shows the largest declines (44%), followed by forage production, carbon storage and tourism viewsheds (25, 27 and 28% reductions); water flow regulation shows the smallest decline of 18% in potential volume of the sustained flows. The non GEOSS scenario finds < 10% declines in most ecosystem services and a 15% decline in the service of erosion control.

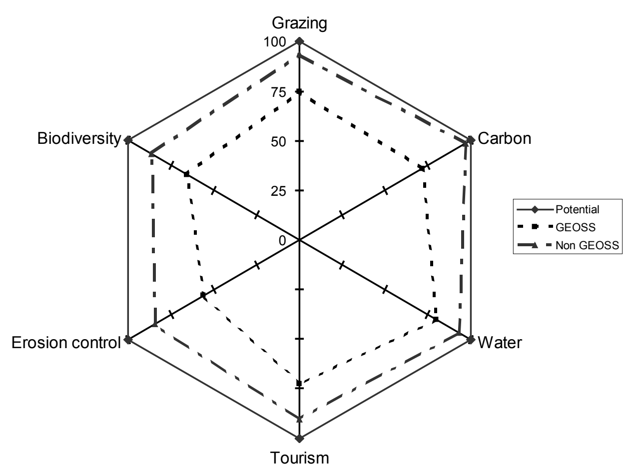

Figure 2: Changes in ecosystem service supply in the Little Karoo, based on GEOSS and non GEOSS scenario databases. Change is reflected as a percentage of the potential supply (nominally that of the pre-colonial period).

When converted these difference between the GEOSS and non GEOSS scenarios (Figure 2) into actual ecosystem service quantities which equate to: over 5000 Large Stock Units, 28 million tons of Carbon, 61 million cubic meters of water, 1000 km^2 of tourism viewsheds and 8 hectares of areas important to erosion control.

4. DISCUSSION

The results of the above GEOSS scenario for ecosystem service and biodiversity assessment provides important information on the current status and capacity of the ecosystems of the Little Karoo, as well as the magnitude of recent changes in these ecosystems and their services. They highlight the substantial impact of land cover change on ecosystem services in the Little Karoo, particularly the impact of extensive overgrazing and subsequent degradation. They point to the fact that past land-use decisions have driven the Little Karoo into a tight corner – with decreased ecosystem service levels, threatened biodiversity, high unemployment levels and narrowing future options for the region and its inhabitants. The assessment provides useful and accurate information on the current state and vulnerabilities of the region's ecosystems and emphasizes the need to make careful land use decisions in the future. It also shows that the region is not meeting its or the country's targets in terms of biodiversity conservation and ecosystem service management.

The results of the non GEOSS scenario assessment tells a very different story of relatively intact ecosystems with biodiversity and ecosystem service levels very similar to what they were during pre-colonial times. It contradicts many studies in the region which highlight the significant declines in ecosystem health and human wellbeing in the region (e.g. Le Maitre *et al*. 2007; O'Farrell *et al*. 2008). The message a decision maker could take from this assessment would be one of good ecosystem state and capacity and little need to change any of the current management practices or land uses.

5. CONCLUSION

For a relatively small investment of 9000 Euros for the GEOSS scenario land cover data (Rouget *et al*. 2006), the study demonstrates substantial improvements in our ability to monitor the condition of the ecosystems of the Little Karoo. It would be useful to be able to contrast this investment with the benefits realized, however the procedure for quantifying the economic benefits of improved environmental information is poorly developed. What we can do is to compare the costs of better data with the costs of bad decisions resulting from absent or weak data. Here Herling *et al*. (In Press) estimate a cost of 2000 euros per hectare to restore overgrazed and degraded land in the Little Karoo. This works out at more than 500 million Euros to restore all severely degraded pieces of land. This is a cost that could potentially have been avoided with good data, early warning and informed management decisions. A further cost related to inappropriate management decisions is the cost of flood damage. In the Little Karoo region floods associated with a cut-off low (a relatively common occurrence in this part of the world) incurred damages to agriculture and infrastructure totaling R35.3 million Euros in 2006. Some of the damages and costs could have been minimized through informed management of human land uses, especially in degraded areas important to erosion control.

The key emergent message from this case study is that small strategic investments in earth observation systems can have disproportionately large effects on our ability to manage biodiversity and ecosystem services. However, determining what the optimal investment in such systems is remains clouded by our inability to quantify the benefits of improved ecosystem management.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Cupido, C.F. 2005. *Assessment of veld utilisation practices and veld condition in the Little Karoo*. Dissertation. University of Stellenbosch, South Africa.

Dean, W.R.J., and S.J. Milton. 2003. Did the flora match the fauna? Acocks and historical change in Karoo biota. *South African Journal of Botany* 69:68-78.

GEO. 2005. Geneva, Switzerland, "Global Earth observation system of systems, 10 year implementation plan reference document" [Online]. Available: http://www.earthobservations.org/documents.shtml

Herling, M. C., C. F. Cupido, P. J. O'Farrell and L. Du Plessis. In Press. The Financial Costs of Ecologically Nonsustainable Farming Practices in a Semiarid System. *Restoration Ecology.*

Le Maitre, D.C., S.J. Milton, C. Jarmain, C.A. Colvin, I. Saayman and J.H.J. Vlok. 2007. Landscape-scale hydrology of the Little Karoo: linking ecosystems, ecosystem services and water resources. *Frontiers in Ecology and the Environment* 5:261-270.

MA (Millennium Ecosystem Assessment). 2005. *Millennium Ecosystem Assessment Synthesis Report.* Island Press, Washington, D.C., USA.

O'Farrell, P.J., D.C. le Maitre, C. Gelderblom, D. Bonora, T. Hoffman and B. Reyers. 2008. Applying a resilience framework in the pursuit of sustainable land-use development in the Little Karoo, South Africa. Pages 383-430 *in* M. E. Burns, and A. v.B. Weaver, editors. *Exploring Sustainability Science – A Southern African Perspective.* SUN PReSS, Stellenbosch, South Africa.

Reyers, B. & McGeoch, M.A. 2007. A Biodiversity Monitoring Framework for South Africa: progress and directions. *South African Journal of Science* 103: 295-300

Reyers, B., P.J. O'Farrell, R.M. Cowling, B.N. Egoh, D.C. Le Maitre and J.H.J. Vlok. *In Press* Ecosystem services, land cover change, and stakeholders:

finding a sustainable foothold for a semi-arid biodiversity hotspot. *Ecology and Society*

Rouget, M., R.M. Cowling, J.H.J. Vlok, M. Thompson and A. Balmford. 2006. Getting the biodiversity intactness index right: the importance of habitat degradation data. *Global Change Biology*, 12:2032-2036.

Scholes, R. J. and R. Biggs. 2005. A biodiversity intactness index. *Nature* 434:45-49.

Thompson, M., J.H.J. Vlok, M. Rouget, M.T. Hoffman, A. Balmford and R.M. Cowling. In Press. Mapping land transformation in a heterogeneous environment: a rapid and cost effective approach for assessment and monitoring. *Journal of Environmental Management*

UNEP (2002a) Report on the Sixth Meeting of the Conference of the Parties to the Convention on Biological Diversity (UNEP/CBD/COP/6/20/Part 2) Strategic Plan Decision VI/26, Convention on Biological Diversity.

Reyers, B., P. J. O'Farrell, R. M. Cowling, B. N. Egoh, D. C. Le Maitre and J. H. J. Vlok 2009. Ecosystem services, land-cover change, and stakeholders: finding a sustainable foothold for a semiarid biodiversity hotspot. *Ecology and Society* **14**(1): 38. [online] URL: http://www.ecologyandsociety.org/vol14/iss1/art38/

Research

Ecosystem Services, Land-Cover Change, and Stakeholders: Finding a Sustainable Foothold for a Semiarid Biodiversity Hotspot

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ABSTRACT. Land-cover change has been identified as one of the most important drivers of change in ecosystems and their services. However, information on the consequences of land cover change for ecosystem services and human well-being at local scales is largely absent. Where information does exist, the traditional methods used to collate and communicate this information represent a significant obstacle to sustainable ecosystem management. Embedding science in a social process and solving problems together with stakeholders are necessary elements in ensuring that new knowledge results in desired actions, behavior changes, and decisions. We have attempted to address this identified information gap, as well as the way information is gathered, by quantifying the local-scale consequences of land-cover change for ecosystem services in the Little Karoo region, a semiarid biodiversity hotspot in South Africa. Our work is part of a stakeholder-engaged process that aims to answer questions inspired by the beneficiaries and managers of ecosystem services. We mapped and quantified the potential supply of, and changes in, five ecosystem services: production of forage, carbon storage, erosion control, water flow regulation, and tourism. Our results demonstrated substantial (20%–50%) declines across ecosystem services as a result of land-cover change in the Little Karoo. We linked these changes in land-cover to the political and land-use history of the region. We found that the natural features that deliver the Little Karoo's ecosystem services, similar to other semiarid regions, are not being managed in a way that recognizes their constraints and vulnerabilities. There is a resulting decline in ecosystem services, leading to an increase in unemployment and vulnerability to shocks, and narrowing future options. We have proposed a way forward for the region that includes immediate action and restoration, mechanisms to fund this action, the development of future economic activity including tourism and carbon markets, and new ways that the science–stakeholder partnership can foster these changes. Although we acknowledge the radical shifts required, we have highlighted the opportunities provided by the resilience and adaptation potential of semiarid regions, their biodiversity, and their inhabitants.

Key Words: *carbon; grazing; human well-being; land degradation; ostriches; tourism; trade-offs; water.*

INTRODUCTION

The last few centuries have seen significant changes in the world's ecosystems, tracking our efforts to: enhance the production of food, fiber, and fuel; control water supplies; and reduce our exposure to natural dangers like predators and storms (Kareiva et al. 2007, Swinton et al. 2007). These efforts have resulted in improvements in the global aggregate of human well-being, with incomes, population sizes, life expectancies, and food supplies showing substantial increases in most parts of the world (Levy et al. 2005). Although the immediate benefits for humans are clear, the ecosystem changes wrought have far-reaching consequences for current and future human well-being (Millennium Ecosystem Assessment (MA) 2005). Understanding these consequences requires an awareness and assessment of the links between ecosystems, their biodiversity, and human well-being. These are mediated through ecosystem services, i.e., the benefits humans obtain from ecosystems (MA 2003).

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Ecosystems provide bundles of ecosystem services that interact with one another in a dependent and nonlinear fashion (Pereira et al. 2005, van Jaarsveld et al. 2005). Decisions to exploit a particular ecosystem service affect the type, magnitude, and mix of services provided by that ecosystem (De Fries et al. 2004, Rodríguez et al. 2006, Bennett and Balvanera 2007). For example, a decision to cultivate an area of land and grow a crop may yield more production services in the form of food or fiber, but can impair the regulatory service of soil retention, decrease the service of water quality regulation, and contribute to eutrophication of aquatic habitats. Ecosystem service trade-offs may have negative consequences for the people dependent on them, and together with the associated erosion of biodiversity, can ultimately undermine the ecosystem service being optimized. The MA presented evidence of the trade-offs being made in the global bundle of ecosystem services and human well-being (MA 2005). It demonstrated that over the past 50 years, enhancements in four of the 24 ecosystem services assessed by the MA (crop production, livestock production, aquaculture, and carbon sequestration) have largely come at a cost to 15 other services assessed (mostly regulating and supporting services). The MA concluded that many of these declines are characteristically nonlinear and abrupt, impact the poorest people, and are often a cause of poverty.

Changes in ecosystems and their services are caused by multiple interacting direct drivers (e.g., land-cover change, climate change, irrigation, or alien invasive species), which in turn are controlled by indirect drivers (e.g., demographic, economic, or cultural changes) (MA 2003). Land-cover change has been highlighted as one of the most important direct drivers of terrestrial ecosystem change (Vitousek et al. 1997, MA 2005). Land-cover change involves changes in the human management of ecosystems (e.g., settlement, cultivation, and grazing) that alter the biogeochemical cycles, climate, and hydrology of an ecosystem. It also drives biodiversity loss through habitat fragmentation and destruction. Land-cover change includes the outright conversion of an area from one land use to another (hereafter referred to as “land transformation”), as well as declines in the biological or economic productivity and complexity of the land as a result of land use or processes related to human activity (hereafter referred to as “land degradation”).

Apart from the work of the MA and its subglobal assessments (Pereira et al. 2005), the consequences of land-cover change for ecosystem services and human well-being have received limited attention at a local scale. Studies are largely descriptive and focus on the trade-offs associated with the optimization of a provisioning service, particularly those services associated with agricultural production (Foley et al. 2005, Bohensky et al. 2006, Rodríguez et al. 2006). Most note qualitative declines in regulating and supporting services, as well as in biodiversity. The few quantitative local-scale studies that have been carried out rely on land-cover change data (derived from remote sensing) and ecosystem service value coefficients (usually extracted from Costanza et al. 1997) to calculate changes in ecosystem service values over time (Kreuter et al. 2001, Zhao et al. 2004, Viglizzo and Frank 2006, Li et al. 2007). Case studies and simulations of land-cover change have also been used to examine the effects on single ecosystem services or processes (e.g., nitrogen levels (Turner et al. 2003), pollination (Priess et al. 2007), livestock production services (O’Farrell et al. 2007), or soil organic carbon (Yadav and Malanson 2008)). The paucity of information on the consequences of land-cover change across multiple ecosystem services, especially at the scale at which management decisions are made, presents a significant obstacle to understanding and managing ecosystems and their services (De Fries et al. 2004).

A further obstacle on this path to sustainable ecosystem management is the process by which information is often derived and used. Many scientists concerned with the complex problems of sustainable development have highlighted that if our final objectives are to foster informed decision making; transform attitudes, behavior, and institutions; and develop appropriate capacity, competencies, and ownership, then the way we conduct our science needs to change (Mitchell et al. 2004, Max-Neef 2005, Hadorn et al. 2006, Knight et al. 2008). They argue that the traditional method of science as a simple research process that provides a solution needs to change to one where science is a social process aimed at resolving a problem through the participation and mutual learning of stakeholders.

With this in mind, we aim to develop information on the local-scale consequences of land-cover change across multiple ecosystem services. We propose to: (1) quantify and map ecosystem services; (2) assess the distribution of ecosystem services, areas of importance to service delivery, and areas of overlap between services; and (3) assess changes in ecosystem service delivery as a result of past land-cover change.

Our research has adopted a method that embeds the ecosystem service assessment in a social process aimed at identifying and implementing strategies for enhancing and safeguarding ecosystem service delivery. The components reported here belong to the assessment phase of this process and will feed into the subsequent planning and management phases outlined by Cowling et al. (2008). The assessment is a structured process that provides knowledge useful for decision makers and managers. It aims to answer questions inspired by the beneficiaries and managers of ecosystem services, providing knowledge useful for mainstreaming ecosystem services into local land-use planning.

Below we detail the study area and its stakeholders, describe the assessment process, present our results, and then discuss their implications for the Little Karoo region and its future. We end with some thoughts on how scientists and stakeholders can build a more sustainable future for the Little Karoo.

METHODS

Study Area: Geography

The Little Karoo region (ca. 19 000 km^2) is a semiarid, intermontane basin where vegetation associated with three globally recognized biodiversity hotspots intersects and intermingles (hotspots include the Succulent Karoo, Maputaland–Pondoland–Albany, and Cape Floristic Region (Mittermeier et al. 2005)). These hotspots are recognized by their high numbers of plant species (especially endemic species), as well as by the significant threats facing these species. Altitude ranges from 400 to >1500 m a.s.l. This plays a major role in determining rainfall, which varies from <200 mm to >1200 mm at high altitudes. High levels of solar radiation (>80%) together with variable rainfall result in potential evapotranspiration of >10 times the rainfall (2250 mm/yr). Mean annual runoff is only 6% of the rainfall and is highly variable, being dominated by episodic flood flows in seasonal systems. The Little Karoo, similar to other semiarid regions of the world, is a region of overall water scarcity. Current demand already exceeds the sustainable supply from dams in the Gouritz River basin, and irrigation uses 90% of the water available (Le Maitre and O'Farrell 2008). The high mountains are of erosion-resistant and highly fractured Table Mountain Group sandstone. They form critical groundwater recharge areas and are the source of most of the perennial rivers and streams in the area.

O'Farrell et al. (2008) present a detailed history of the region's land use and highlight that the major form of land use has been, since the 1730s, extensive grazing and browsing by livestock (chiefly ostriches, but also sheep and goats). Very little (<10%) outright transformation of natural habitat to cultivated areas has taken place. This has been limited to areas with shale-derived soils and sufficient rain for dryland cultivation, and alluvial habitats with access to irrigation water (Fig. 1; Thompson et al. 2009). However, degradation of vegetation and soil through overgrazing is the main driver of land-cover change and biodiversity loss in the area. Historical records indicate that certain districts in this region have been heavily overstocked by cattle, horses, donkeys, sheep, goats, and ostriches (Dean and Milton 2003), leaving large areas (52%) of degraded land in the Little Karoo (Thompson et al. 2009). Rouget et al. (2006) and Gallo et al. (2009) demonstrate that degradation and clearing for croplands have resulted in a 35% decline in biodiversity condition in the Little Karoo, and 20% of the area being recognized as threatened ecosystems.

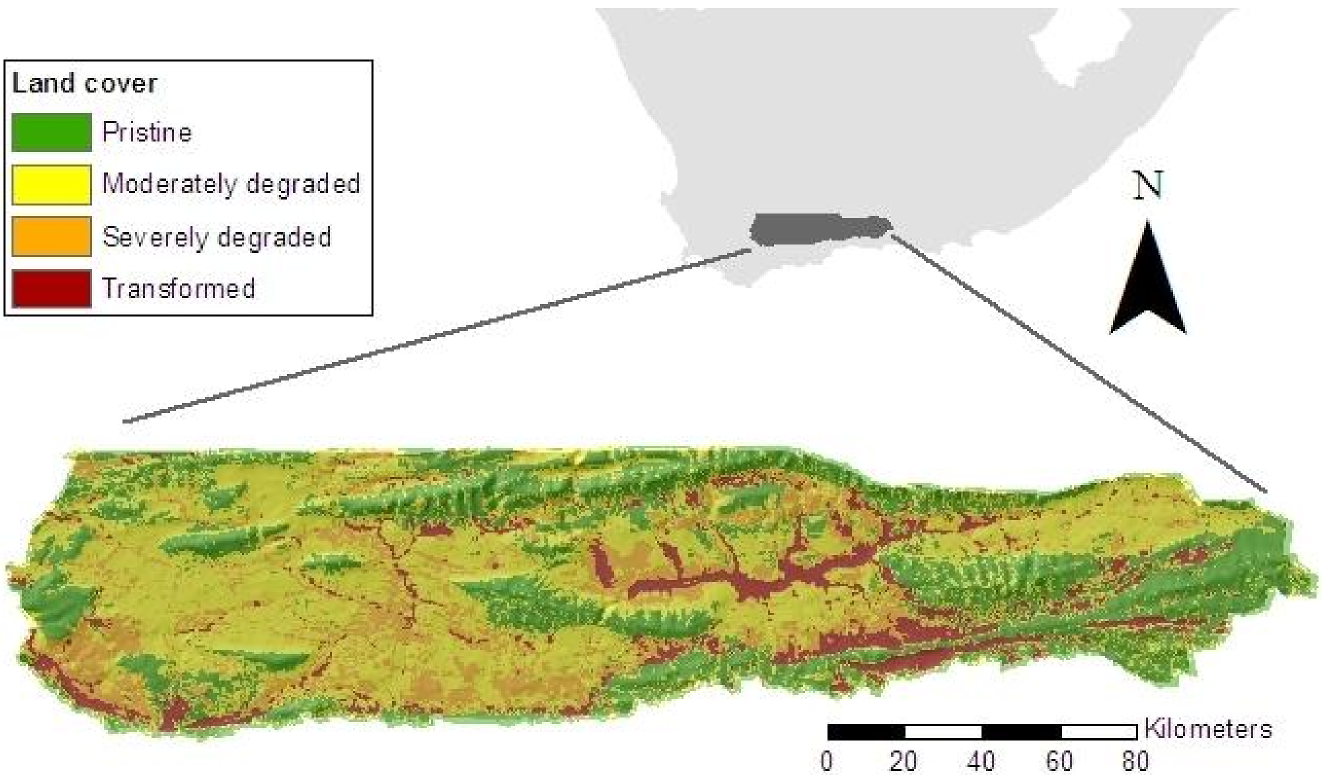
The high biodiversity value of the area, along with the pressures on this biodiversity, have resulted in the Little Karoo being identified as an area of conservation importance by three internationally funded conservation and development programs (the Cape Action Plan for People and the Environment, the Subtropical Thicket Ecosystem Program, and the Succulent Karoo Ecosystem Plan), each of which identified a suite of projects for achieving conservation-related objectives in the Little Karoo.

Study Area: Governance and Stakeholder Environments

Environmental governance in South Africa is complex, spanning many sectors as well as national, provincial, and local spheres of government. Although national and provincial governments have concurrent legislative competence for environmental management, it is at the local municipal scale that land and natural resource use decisions are made

Figure 1. Study area of the Little Karoo illustrating its position in South Africa, as well as the current land-cover situation.

Note: Transformed areas are those that have been converted to cropland and urban areas. Distinction is drawn between areas of moderate and severe degradation where the former can be restored with the removal of grazing pressure, whereas the latter will require restoration actions to restore the plant communities. The map is transposed over a digital elevation model for illustrative purposes.



Thompson et al. 2008

and implemented (Pierce et al. 2005). The Little Karoo encompasses portions of five local municipalities. Despite some innovative legislation, institutions, and processes, as well as budgetary increases, capacity and finances still appear to be insufficient to meet the demands of the crosscutting cooperative governance required for environmental management (Department of Environmental Affairs and Tourism 2006). This is particularly the case at provincial and municipal levels and remains a major obstacle to achieving sustainable development targets.

In recognition of the significant conservation challenges and the concurrent governance challenges facing the region, the Gouritz Initiative (GI) was established. It was set up in 2003 in order to coordinate strategies, facilitate co-governance, build capacity through mutual learning, and accommodate the needs of a diverse array of stakeholders. Its mission is to "...take ownership of the sustainable utilization of the unique biodiversity of the area by ensuring global recognition through partnerships, continuous awareness and responsible decision making for the benefit of all people, now and in the future."

The GI is coordinated by a steering committee with representation from all key partners including government departments, landowners, non-governmental organizations, and municipalities. There is also a GI Forum where a larger number of stakeholders (including landowners, business representatives, and scientists) meet and discuss issues of concern. Under the auspices of the GI, the Little Karoo Study Group was established to undertake research identified as important by the GI Forum. This study group comprises eight research institutions and five implementing agencies collaborating on research projects to support and promote sustainable development and the wise use of ecosystem services in the Little Karoo.

This study has arisen from the interaction between the GI Forum and the Little Karoo Study Group, precipitated by concerns expressed in the GI Forum around: the increase in the extent and intensity of degradation of the land by increased livestock (particularly ostrich) numbers (O'Farrell et al. 2008); concerns about flood damage (Eden District Municipality 2008); problems regarding water security and intentions to mine fossil water (Le Maitre et al. 2007); and the increasing importance of tourism as an economic sector. The stakeholder forum requested the study group to conduct an assessment of the natural features (ecosystem services) that support the ostrich and tourism industries, as well as those that regulate floods and water supplies. This assessment would form the first step of a stakeholder forum exercise to identify opportunities and constraints in working toward a sustainable future.

Assessment: Mapping Potential Ecosystem Services

The Little Karoo has been the site of much research in the last few years, which has resulted in some key databases essential to the study of ecosystem services (Vlok et al. 2005, Le Maitre et al. 2007, O'Farrell et al. 2008, Thompson et al. 2009). Of particular value to this study is a map of vegetation types mapped at a 1:50 000 scale (Vlok et al. 2005). This map was developed in order to inform decision making about conservation, sustainable commercial farming, and land-use planning matters in the region. Accordingly, it mapped 369 vegetation units on the basis of their floristic composition. The vegetation units were classified into 32 habitat types relevant to the agricultural and wildlife industries in the region, by considering their physiognomy as well as the floristic component of the vegetation units (Vlok et al. 2005). The habitat types are nested within six biomes: Subtropical Thicket, Succulent Karoo, Renosterveld, Fynbos, Aquatic Drainage, and Aquatic Source.

The spatial extent of land transformation and degradation of the Little Karoo has also been mapped at a 1:50 000 scale (Fig. 1; Thompson et al. 2009). This map depicts areas of pristine vegetation and transformed (cultivated and urban) areas, and importantly, it also maps moderately and severely degraded areas. Moderately degraded areas are those areas where, although the plant communities have been impacted by grazing, this impact is limited mainly to the trampling and degradation of biotic crusts, some soil loss, and declines in the populations of palatable species. Removal of grazing pressure would allow these communities to return to a near pristine state. In contrast, severely degraded areas have been substantially overgrazed and have no biological soil crusts, severe soil loss, and totally altered plant communities (complete loss of palatable species). These areas require restoration actions to re-establish the communities and ecosystem function. The four categories of land cover (pristine, moderately degraded, severely degraded, and transformed) will have different consequences for the ecosystem services provided by a parcel of land. As the land-cover data were only available for 2005, our analyses are based on the difference between the 2005 data and the precolonial condition where all areas are assumed to be pristine (Scholes and Biggs 2005).

Our work is based on a suite of ecosystem services identified by the GI Forum as being of importance in this area. Carbon storage was not identified by the forum, but was included based on the potential opportunities it presents for restoration activities (Mills and Cowling 2006). The five services we have examined are: (1) production of forage for domestic livestock; (2) carbon storage; (3) erosion control; (4) freshwater flow regulation; and (5) tourism.

Rationales and descriptions of each ecosystem service are presented below (details on the methods used to map the services are available in Appendix 1). We first map the potential delivery of ecosystem services, presuming all areas are pristine. When mapping the ecosystem services and assessing the consequences of land-cover change, we relied on a diversity of available data sources ranging from peer-review literature to expert consultation. This reliance on available and diverse data has important implications when interpreting the findings of this study. In outlining the methods used in Appendix 1, we follow the procedure of the MA by assigning levels of certainty to each ecosystem service map based on the type and amount of data, as well as the strength of review or consensus.

Potential forage production

Livestock production is the most important economic activity and employer in the Little Karoo, although its economic importance has declined (Le Maitre and O’Farrell 2008). Forage production is defined as the provision of forage for grazing rangeland livestock. We mapped this as hectares required per large stock unit (LSU) per habitat type.

Potential carbon storage

The Little Karoo includes components of the Subtropical Thicket biome, which is particularly vulnerable to overgrazing (Hoffman and Cowling 1990); in fact, overgrazing has left 19.6% and 62.1% of the biome in the Little Karoo severely and moderately degraded, respectively (Thompson et al. 2009). Of relevance to this study is that the biome shows unusually high rates of carbon sequestration (Mills et al. 2005) and demonstrates significant potential for restoration through the use of carbon credits and other payments for ecosystem services (Mills and Cowling 2006). This ecosystem service was mapped as tons of carbon stored per hectare per habitat type.

Potential erosion control

The weather patterns in this area (most notably the cutoff lows) result in frequent floods, which have an enormous impact on the region’s economy (Eden District Municipality 2008). Overgrazing and subsequent degradation have resulted in increases in surface runoff, changes in flow and groundwater regimes, decreases in water quality, and increases in the severity and frequency of floods (Le Maitre et al. 2007). Natural ecosystems play a vital role in ameliorating these impacts by retaining soils and preventing soil erosion. The ecosystem service of erosion control depends mainly on the structural aspects of ecosystems (especially vegetation cover and root systems) and includes the protection of the soil, as well as the maintenance of water quality in nearby water bodies (de Groot et al. 2002). Areas requiring this service are those vulnerable to erosion, as determined by the rainfall, soil depth, and texture. We have mapped this vulnerability as areas of high, medium, and low erosion hazard. The former corresponds with areas where natural vegetation cover must be maintained to control erosion.

Potential water-flow regulation

The Little Karoo is a water-limited environment with water availability restricting rangeland production, as well as dryland and irrigated farming, which are the basis of the economy (Le Maitre and O’Farrell 2008). A number of previous studies have used the volume of water as a measure of the service of water provision (van Jaarsveld et al. 2005, Chan et al. 2006), but we have used a narrower definition because the volume is largely a function of the amount and distribution of rainfall (Bosch and Hewlett 1982, Calder 1998). We focus on two distinct and interlinked roles the ecosystem plays in the service of water provision: water-flow regulation and water-quality regulation (de Groot et al. 2002). The ecosystem service was mapped as millions of cubic meters of groundwater recharge per 1-km^2 grid cell.

Potential tourism

Tourism is becoming increasingly important in this region, and many landowners are turning to accommodation and recreational opportunities on their land as alternative income sources. The region is popular for its wide open spaces and scenery. This ecosystem service was mapped as areas that tourists can see from the major tourist driving routes, which are important to maintain in an attractive form for tourists.

Assessment: Service Distribution, Overlap, and Change

The maps of ecosystem services were evaluated in terms of their area of production and overlap with one another. For the purposes of display and comparison, each map of ecosystem services was classified into high, medium, and low production classes. For the continuous variable maps of carbon storage, forage production, and water-flow regulation, the classes were determined using a Jenks natural breaks classification in ArcGIS® 9.2 (Environmental Systems Research Institute 2008). For the erosion control and tourism maps, all areas of high erosion hazard and areas of viewshed were included as high production areas, respectively. Overlap was assessed between high production areas (hereafter referred to as service hotspots (following Egoh et al. (2008)) and was measured using proportional overlap (Prendergast et al. 1993), which measures the area of overlap as a percentage of the smallest hotspot. An assessment of ecosystem service condition was conducted by analyzing the percentage of the four categories of land cover (pristine, moderately degraded, severely degraded, and transformed) within each ecosystem service hotspot.

To convert land-cover statistics into measures of ecosystem service change, we developed a matrix of the extent to which the transformed and degraded categories of land cover diminished the delivery of each of the quantified ecosystem services. Estimates were based on expert knowledge for forage production and freshwater-flow regulation, and a mix of expert knowledge and literature sources for carbon storage (Mills et al. 2005). This was done at the habitat level for the services of forage production and carbon storage, and at the biome level for water-flow regulation. Appendix 2 shows the ecosystem service values per habitat type and land-cover category for forage production and carbon storage. Appendix 3 shows the values for water-flow regulation per biome. The values were reviewed by relevant experts, and we have assigned a medium certainty to the matrix due to limited empirical data. We assumed that cultivated and urban areas could not reliably provide these services. We acknowledge the flaws in this assumption as these areas are able to produce some levels of services (see Colding et al. 2006); however, we were unable to determine the residual service amounts provided by these areas and, therefore, assumed them to be zero.

Using a GIS, we calculated the amount of each ecosystem service (forage production, carbon storage, and water-flow regulation) provided under current land-cover conditions by multiplying the area of each habitat type or biome within each land-cover category by the values listed in Appendices 2 and 3. For the services of erosion control and tourism, we calculated the area of high erosion control and viewsheds in pristine or moderately degraded land-cover categories and assumed that only these areas could provide the services currently. We converted the changes in each ecosystem service into proportions of the potential service in order to make the changes comparable; we used the values to develop spider diagrams (such as those used in MA 2003, De Fries et al. 2004, and Rodríguez et al. 2006) to depict the changes in ecosystem service supply.

RESULTS

Potential Ecosystem Services in the Little Karoo

Figure 2 shows the distribution of the potential supply of five ecosystem services and the service hotspots in the Little Karoo. Table 1 presents the extent of service hotspots and overlap between hotspots across services. It is clear that high levels of supply of ecosystem services are limited to a few areas; service hotspots occupy only 10%–38% of the region. Water-flow regulation, erosion control, and carbon storage have particularly small service hotspots (Table 1). Furthermore, there appears to be limited congruence between service hotspots with proportional overlap <40%, with the exception of forage production and erosion control, which share 76% of their hotspots (Table 1). Carbon storage shares no hotspots with erosion control and very little (0.04%) with water-flow regulation. The larger service hotspots of tourism and forage production show the highest congruence with other ecosystem service hotspots.

Forage production and carbon storage, although both produced in lowland areas, are associated with different biomes: the former is spread across the Thicket, Succulent Karoo, and Renosterveld biomes, whereas the latter is found in the central and eastern Thicket areas. Areas of importance to erosion control are located in both montane and lowland areas in regions of high runoff (source) and run-on (drainage) areas, as well as in the Gannaveld vegetation (a vegetation type of high forage production) of the Little Karoo. Areas with high groundwater recharge, and thus the sources of sustained river flows, are limited to the mountains and concentrated at elevations higher than 1000 m a.s.l. Areas of importance to tourism are determined by a combination of topography and road networks and are primarily found in the central regions and along mountain passes.

Figure 2. Maps of potential ecosystem services of the Little Karoo illustrating: (a) Forage production: number of hectares required by a large stock unit (LSU) in each habitat type; (b) Carbon storage: tons of carbon stored per hectare of each habitat type; (c) Water-flow regulation: volume of water provided by a 1-km^2 grid; (d) Erosion control: areas of high, medium, and low erosion hazard requiring the maintenance of natural vegetation cover; and (e) Tourism: 10-km viewshed seen by tourists from the major tourist routes.

Note: All maps are transposed over a digital elevation model for illustrative purposes.

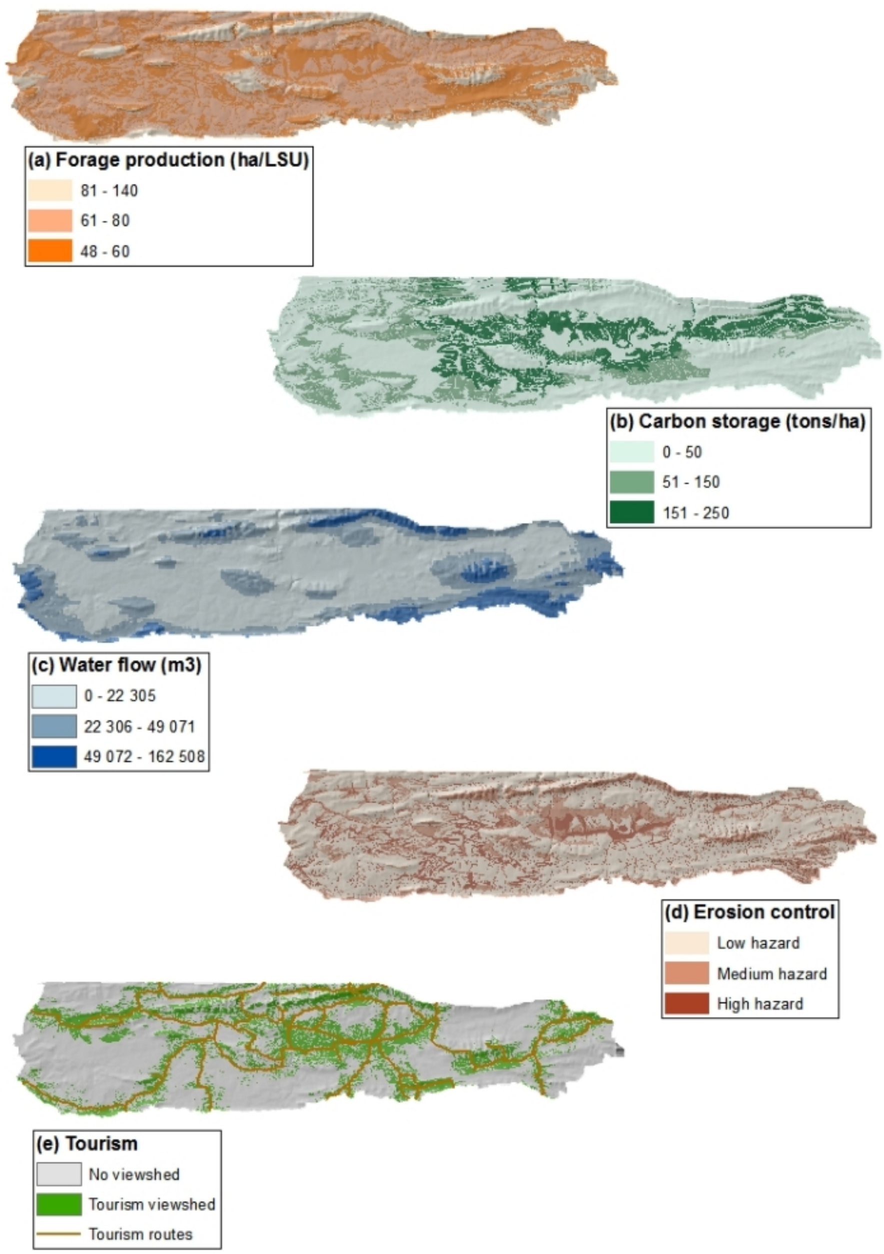


Table 1. Extent and proportional overlap of ecosystem service hotspots.

Ecosystem service	Proportional overlap between ecosystem service hotspots				Hotspot area
	Carbon	Erosion	Water	Tourism	(% of study area)
Forage	21.52	76.37	29.70	39.46	37.84
Carbon		0.00	0.04	33.85	16.64
Erosion			13.08	25.30	14.50
Water				33.44	10.82
Tourism					29.39

Ecosystem Services Changes in the Little Karoo

Table 2 illustrates the land-cover situation in each of the five ecosystem service hotspots. Carbon storage and erosion control have very little of the service hotspots remaining in a pristine condition (12% and 20%, respectively). Water-flow regulation hotspots include the highest proportion of pristine land cover (81%), followed by forage production (41%) and tourism (39%). Moderately degraded areas cover approximately one-third of all ecosystem service hotspots, with the exception of water production (4%) and carbon storage (74%). Erosion control hotspots have been 26% transformed.

The large proportion of the study region and ecosystem service hotspots that are currently transformed or degraded (Fig. 1, Table 2), as well as the changes in ecosystem services caused by land-cover changes (Appendices 2, 3), result in large declines across all ecosystem services (Fig. 3). Compared with potential service supply, erosion control shows the largest declines (44% of the erosion control hotspot had lost its vegetation cover), followed by forage production, carbon storage, and tourism viewsheds (25%, 27%, and 28% reductions in LSU, area attractive to tourists, and tons of carbon, respectively). Water-flow regulation shows the smallest decline (18%) in potential volume of the sustained flows. The services showing greatest declines are those delivered by the lowland and foothill regions that have been transformed to cultivated areas or overgrazed and subsequently severely degraded.

DISCUSSION

Service Declines, Degradation, and Increasing Vulnerability in the Little Karoo

Our work highlights the substantial impact of land-cover change on ecosystem services in the Little Karoo, resulting in declines ranging from 18%–44% in ecosystem service levels. These declines mirror biodiversity losses in the region found by Rouget et al. (2006) and Gallo et al. (2009). Of particular concern to the region's future sustainability is the 18% decline in the water-flow regulating service and the 44% decline in areas responsible for erosion control. The significance of these declines relates to the semiarid nature of the Little Karoo, as well as the overarching role regulating services play in soil conservation and nutrient cycling, and in turn, the services of primary production and water provision (Safriel et al. 2005). It is the latter services that underpin the agricultural economy of semiarid systems like the Little Karoo.

These results also point to the substantial impacts of the extensive areas of degraded land. Degraded areas, which make up 52% of the region, overlap with more than 40% of the hotspots of the carbon, forage, erosion, and tourism services. Overgrazing of these areas, together with clearing of other areas

Table 2. Land-cover composition of ecosystem service hotspots shown as a percentage of the total hotspot.

	Ecosystem service hotspot				
Landcover category	Forage	Carbon	Erosion	Water	Tourism
Pristine	**40.95**	12.40	19.76	**81.26**	**39.41**
Moderate	31.75	**73.99**	**36.00**	4.42	33.32
Severe	11.17	10.22	18.36	6.45	12.83
Transformed	16.12	3.38	25.88	7.87	14.43

Note: Bold values indicate the highest value per service.

to grow livestock feed to supplement the forage production service, have been major drivers of change in ecosystem services in the Little Karoo.

The declines in what are mostly regulating and supporting services, together with the documented biodiversity losses, raise concerns about long-term decreases in the region's productivity and resilience, and thus increases in its vulnerability to shocks such as floods, drought, or market shifts. It is evident that past land-use decisions have driven the Little Karoo into a tight corner. The region is facing decreased ecosystem service levels, threatened biodiversity, high unemployment levels, and narrowing future options. The situation mirrors semiarid regions around the world, which house the most vulnerable people, ecosystems, and ecosystem services (MA 2005).

Understanding the drivers of changes in land cover and subsequently in ecosystem services is essential in the design of interventions. Below, we reflect on the history of land use in the Little Karoo in an effort to extract key drivers of change for the purposes of potential intervention.

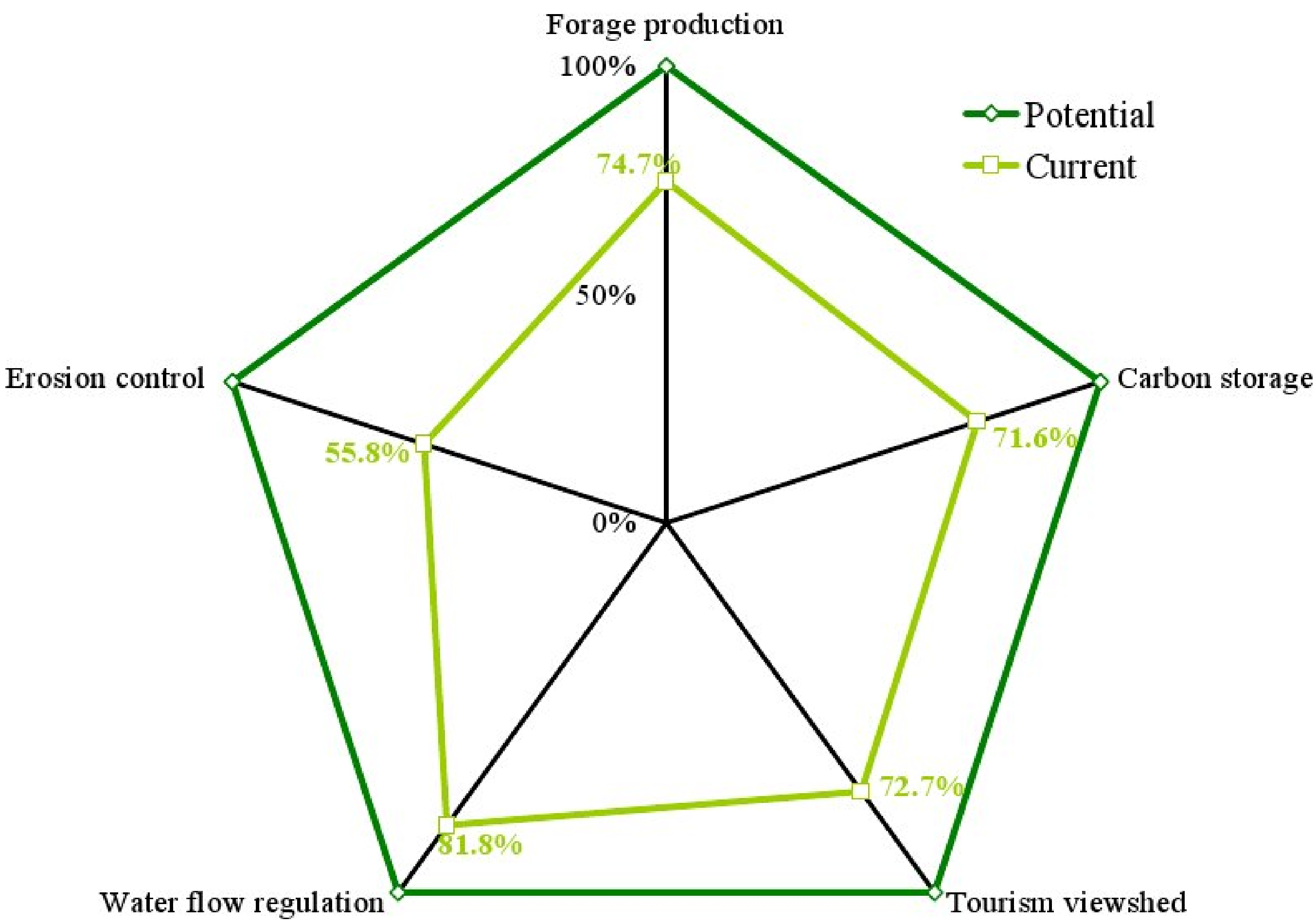
Building a Sustainable Future: Understanding Drivers of Change

The political, social, economic, and technological changes associated with the colonial period (1652–1910), as well as the Union and Apartheid eras (1910–1994), were key drivers of change in the Little Karoo. These changes caused a switch from a system of transhumance pastoralism and subsistence farming to one of permanent commercial agriculture (O' Farrell et al. 2008). Of particular relevance are two major changes in land use that took place in the 1800s. The first was the beginning of ostrich farming in the region, and the second was the proclamation of nutrient-poor, montane areas as protected water catchments in the 1870s (Beinart 2003). Ostrich farming had negative and ongoing repercussions for the region's ecosystem services, and the protection of important water catchment areas helped to limit transformation and overgrazing.

The ostrich industry in the Little Karoo was initiated in the early to mid 1800s for the production of feathers. Over the next two centuries, the numbers of birds in the Little Karoo fluctuated radically due to outbreaks of avian diseases and changes in fashion and tastes. The deregulation of the industry in 1996, along with growing demand for ostrich meat, resulted in a dramatic increase in the number of ostriches. Census estimates for 2002 included 250 000 birds sales and 150 000 birds on farms in the Little Karoo. These ostrich numbers alone total more than five times the total potential capacity of 27 000 LSU in the Little Karoo (Fig. 2a; one ostrich = 0.35 LSU). This situation typifies current agricultural practices in the region, which have shifted away from traditional crop and livestock production to the production of ostriches and their main feed, lucerne. Ostriches have a significant impact on rangeland vegetation because they pull

Figure 3. Changes in ecosystem service supply shown as a percentage of the potential service produced in the Little Karoo.

Note: The data labels show the current levels of ecosystem services as a percentage of the potential.



out plants rather than biting off foliage. In addition, trampling and territorial displays lead to soil compaction, the removal of the biological soil crust, and the formation of pathways that channel surface water (Cupido 2005). These impacts, together with the impacts of extensive sheep farming, have resulted in most of the changes in land cover and declines in ecosystem services shown in Fig. 3. Other associated impacts of overgrazing (which include salinization, soil loss, sedimentation, declines in water quality, and reductions in nitrogen input) will further undermine the future productivity of the system.

The history of land-use decisions and their impacts in the Little Karoo point to the need to manage systems in ways that recognize their natural constraints and vulnerabilities, as well as the need to create future economies and livelihoods that foster sustainable use of services along with the promotion of human well-being. Sustainable land-use practices rely on the consideration of, and protection of, ecosystems and their services. Such practices focus on maintaining the resilience of ecosystems, and on building agility into production strategies, enabling responses to market trends and fluctuations. Based on our research, we outline below some recommendations aimed at building sustainable landscapes in the Little Karoo.

Building a Sustainable Future: Who Pays?

Creating a sustainable Little Karoo will require improvements in the current condition of its ecosystems and their services. This, in turn, will require large-scale conservation and restoration activities targeted at areas of importance to water-flow regulation and erosion control (unfortunately these display very little overlap; see Table 1). This realization is not new and, as far back at the 1930s, the government formulated policies to deal with drought and erosion. However, the lack of policy coordination and alignment, the short duration of successful legislation (Beinart 2003, Dean and Roche 2007), and the slow pace of ecosystem recovery, leave the Little Karoo districts as some of the most degraded areas in the Western Cape Province of South Africa (Hoffman and Ashwell 2001).

The global significance of the region's biodiversity, along with its threatened state, have attracted local and international investment in conservation programs, including the establishment of the GI, the development of management guidelines for the ostrich industry, and the establishment of a biodiversity tourist route and catchment management projects. However, the scale of the challenges makes it essential that the efforts extend beyond just the conservation sector to other sectors, landowners, and even new funding mechanisms.

The short-term opportunity costs for farmers, discount rates, and cost of restoration programs (along with their sometimes low likelihood of success) (Wiegand et al. 1995, Herling et al. 2009) make restoration efforts by private landowners currently unfeasible. This echoes the lament of Ruhl et al. (2007) that there are no incentives for rational people to safeguard something they own, because doing so will deliver, in uncertain ways and perhaps only some time in the future, benefits to others who live somewhere else.

An alternative funding mechanism that deserves investigation is the “Payment for Ecosystem Services” (PES). These PES projects have shown some potential in South Africa in public-funded poverty relief programs that clear invasive alien plants and restore hydrological function (Turpie et al. 2008). They have also aided in the design of internationally and nationally funded restoration programs in the Drakensburg mountains (Blignaut et al. 2008). The advent of carbon markets broadens the funding mechanisms available for these schemes, given the high carbon sequestration values in parts of the Little Karoo (Mills et al. 2005), along with the degraded state of its carbon hotspots. However, of note is that areas of carbon storage potential show low levels of overlap with areas important to other ecosystem services (Table 1). Furthermore, as Ruhl et al. (2007) and Blignaut and Aronson (2008) point out, PES schemes require a fundamental shift in the way the existing institutions and legal, policy, and accounting frameworks currently operate. Once we have adopted these (currently radical) shifts, then perhaps restoration of the ecosystems and ecosystem services of the Little Karoo will begin to make sense.

Building a Sustainable Future: Economies of the Future

In addition to improvements in the current condition of the ecosystems and services of the Little Karoo, alternatives to the current high-density livestock livelihoods will need to be identified and investigated. In assessing alternative land uses, our work has highlighted two characteristics of the region's ecosystem services that might be of use: (1) the key role that water services play in the system, and (2) the potential of carbon storage and tourism for the future economy of the region.

Water-flow regulation is a crucial service in the Little Karoo, with effects that cascade throughout the entire system and its services. It underpins the productivity of the system and determines its vulnerability to future change. The currently degraded state of water services, along with the heavy reliance of current land uses on water, point to a need to consider future land uses that promote efficient water use, and land management that ensures maximum sustained water yields and quality.

Carbon storage and tourism ecosystem services provide opportunities for landowners to diversify their income streams and the potential for them to make money from their land without having to overstock it with ostriches. With regard to stimulating a carbon economy in the region, research is currently underway to assess the carbon sequestration rates associated with experimental plantings of spekboom (*Portulacaria afra*) in a wide range of spekboom-dominated thicket habitats throughout the region. This will assess the extent to which the promising findings regarding the viability of restoration for carbon credits documented by Mills and Cowling (2006) apply throughout the Little Karoo. Excellent progress has been made with developing documentation for participation in the formal carbon market (through the Kyoto Protocol's Clean Development Mechanism [CDM]) in a region that forms the northeastern boundary of the Little Karoo (A. J. Mills, personal communication). Owing to the considerable transaction costs, developing access to the formal and informal carbon markets needs to parallel the ecological research on sequestration rates. There are plans to do precisely this.

Tourism is developing rapidly in the area, and many landowners earn additional income from accommodation and recreation opportunities. Several land purchases in the region over the last 10 years have been made in order to create tourist features such as private luxury game parks (O'Farrell et al. 2008). There are concerns that land managed for tourism is not synonymous with land managed for conservation due to the differences in contractual commitments as well as management regimes. However, several studies highlight the potential that privately owned areas can play in safeguarding ecosystems and their services, especially if partnered with useful information, incentives, and management guidelines (Fitzsimons and Westcott 2008, Gallo et al. 2009).

Building a Sustainable Future: Science in Partnership with Stakeholders

The path to a sustainable Little Karoo will be a challenging one, requiring changes in land use, policies, behavior, institutions, markets, accounting systems, and incentive schemes. Our results also point to a need for urgent change in current land-use activities if some future options are to be kept open for the region and its people. The required changes would be even more daunting if the stakeholders in the region were neither convinced of the need for change nor in agreement on a way forward. A forum and a social process have been provided through the GI for stakeholders to express their information needs, and for scientists to engage with the stakeholders, respond to their needs, present their work, and discuss its results. Recognizing the importance of socially engaged science (van Kerkhoff and Lebel 2006, Cowling et al. 2008), we feel that this represents an important first step on this path to sustainability. Furthermore, the GI Forum has proved to be a useful method for fostering agreement on the problem to be solved, and promoting co-governance through agency representation on (and learning from) the forum.

Although acknowledging that there will invariably be complexity and uncertainty associated with the study of multiple ecosystem services, we feel that field measurements of the impacts of land-cover change on ecosystem services should be an important focus for the Little Karoo Study Group in the future. Field measurements would allow us to groundtruth expert estimates and extrapolations, as well as fill in the gaps around service flows for urban and cultivated systems. The low certainty attached to carbon storage services makes them a priority, where ongoing and future research will improve certainty in this service, concerning the impacts of degradation on the service and an understanding of how to move from carbon storage to carbon sequestration (Mills and Cowling 2006).

In addition to research into carbon sequestration, new projects have arisen through the GI, the forum, and the study group. One of these aims to convert the information developed in our research into user-useful and user-friendly products (mainstreaming, as exemplified by Pierce et al. 2005) to be distributed to management agencies and landowners in hard copy and over the internet (http://www.gouritz.com). Another planned project follows the operational framework outlined by Cowling et al. (2008) for mainstreaming and safeguarding ecosystem services and moves forward into the collaborative development of scenarios, strategic objectives, and actions for the Little Karoo.

CONCLUSION

Safriel et al. (2005) reflect on the historic ability of societies in semiarid systems to cope and adapt to their harsh environment. Social resilience, knowledge evolution, and successful farmer adaptation have played a key role in this ability to cope much better than non-dryland farmers at similar levels of human well-being. This competitive edge, partnered with the significant biodiversity found within semiarid systems, leaves

Safriel and his colleagues feeling optimistic about the potential for these social–ecological systems to alleviate the current low levels of human well-being. We remain hopeful that the Little Karoo too can follow this course, but acknowledge that the individual, economic, institutional, and political requirements are significant and wide ranging, and for the most part, are not currently in existence.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol14/iss1/art38/responses/

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LITERATURE CITED

Beinart, W. 2003. The rise of conservation in South Africa: settlers, livestock and the environment 1770–1950. Oxford University Press, New York, New York, USA.

Bennett, E. L., and P. Balvanera. 2007. The future of production systems in a globalized world. *Frontiers in Ecology and the Environment* **5**:191–198.

Blignaut, J., and J. Aronson. 2008. Getting serious about maintaining biodiversity. *Conservation Letters* **1**:12–17.

Blignaut, J., J. Aronson, M. Mander, and C. Marais. 2008. Investing in natural capital and economic development: South Africa’s Drakensberg Mountains. *Ecological Restoration* **26**(2):143–150.

Bohensky, E., B. Reyers, and A. S. van Jaarsveld. 2006. Future ecosystem services in a southern African river basin: reflections on a scenario planning experience. *Conservation Biology* **20**(4):1051–1061.

Bosch, J. M., and J. D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* **55**:3–23.

Calder, I. R. 1998. Water use by forests, limits and controls. *Tree Physiology* **18**:625–631.

Chan, K. M. A., M. R. Shaw, D. R. Cameron, E. C. Underwood, and G. C. Daily. 2006. Conservation planning for ecosystem services. *PLoS Biology* **4** :(11:e379). doi:10.1371/journal.pbio.0040379.

Colding, J., J. Lundberg and C. Folke. 2006. Incorporating green-area user groups in urban ecosystem management. *Ambio* **35**(5):237–244.

Costanza, R., R. d’Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. V. O'Neil, J. Paruelo, R. G. Raskin, P. Sutton, and van M. van den Belt. 1997. The value of the world’s ecosystem services and natural capital. *Nature* **387**:253–260.

Cowling, R. M., B. Egoh, A. T. Knight, P. J. O’Farrell, B. Reyers, M. Rouget, D. Roux, A. Welz, and A. Wilhelm-Rechman. 2008. An operational model for mainstreaming ecosystem services for implementation. *Proceedings of the National Academy of Sciences* **105**(28):9483–9488.

Cupido, C. F. 2005. Assessment of veld utilisation practices and veld condition in the Little Karoo. Dissertation, University of Stellenbosch, Stellenbosch, South Africa.

De Fries, R. S., J. A. Foley, and G. P. Asner. 2004. Land-use choices: balancing human needs and ecosystem function. *Frontiers in Ecology and the Environment* **2**:249–257.

de Groot, R., M. A. Wilson, and R. M. Boumans. 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics* **41**:393–408.

Dean, W. R. J., and S. J. Milton. 2003. Did the flora match the fauna? Acocks and historical change in Karoo biota. *South African Journal of Botany* **69**:68–78.

Dean, W. R. J., and C. J. Roche. 2007. Setting appropriate targets for changed ecosystems in the semiarid Karoo, South Africa. Pages 57–63 *in* J.

Aronson, S. J. Milton, and J. N. Blignaut, editors. *Restoring natural capital. science, business, and practice.* Island Press, Washington, D.C., USA.

Department of Environmental Affairs and Tourism (DEAT). 2006. A report on the state of the environment. South Africa Environment Outlook. Department of Environmental Affairs and Tourism, Pretoria, South Africa.

Eden District Municipality (EDM). 2008. Revised integrated development plan 2008/2009. [online] URL: http://www.edendm.co.za.

Egoh, B., B. Reyers, M. Rouget, D. M. Richardson, and A. S. van Jaarsveld. 2008. Mapping ecosystem services for planning and management. *Agriculture, Ecosystems and Environment* **127**:135–140.

Environmental Systems Research Institute (ESRI). 2008. ArcGIS Desktop (ArcInfo) Software. ESRI, Redlands, California, USA.

Fitzsimons, J. A., and G. Wescott. 2008. The role of multi-tenure reserve networks in improving reserve design and connectivity. *Landscape and Urban Planning* **85**:163–173.

Foley, J. A., R. DeFries, G. P. Asner, C. Barford, G. Bonan, S. R. Carpenter, F. S. Chapin, M. T. Coe, G. C. Daily, H. K. Gibbs, J. H. Helkowski, T. Holloway, E. A. Howard, C. J. Kucharik, C. Monfreda, J. A. Patz, I. C. Prentice, N. Ramankutty, and P. K. Snyder. 2005. Global consequences of land use. *Science* **309**:570–574.

Gallo, J. A., L. Pasquini, B. Reyers, and R. M. Cowling. 2009. The role of private conservation areas in biodiversity representation and target achievement within the Little Karoo region, South Africa. *Biological Conservation* **142**:446–454.

Hadorn, G. H., D. Bradley, C. Pohl, S. Rist, and U. Wiesmann. 2006. Implications of transdisciplinarity for sustainability research. *Ecological Economics* **60**(1):119–128.

Herling, M. C., C. F. Cupido, P. J. O'Farrell, and L. Du Plessis. 2009. The financial costs of ecologically nonsustainable farming practices in a semiarid system. *Restoration Ecology, in press.* DOI: 10.1111/j.1526-100X.2008.00419.x

Hoffman M. T., and R. M. Cowling. 1990. Desertification in the lower Sundays River Valley, South Africa. *Journal of Arid Environments* **19**:105–117.

Hoffman, T., and A. Ashwell. 2001. Nature divided: land degradation in South Africa. University of Cape Town Press, Cape Town, South Africa.

Kareiva, P., S. Watts, R. McDonald, and T. Boucher. 2007. Domesticated nature: shaping landscapes and ecosystems for human welfare. *Science* **316**:1866–1869.

Knight, A. T., R. M. Cowling, M. Rouget, A. Balmford, A. T. Lombard, and B. M. Campbell. 2008. "Knowing" but not "doing": selecting priority conservation areas and the research-implementation gap. *Conservation Biology* **22**:610–617.

Kreuter, U. P., H. G. Harris, M. D. Matlock, and R. E. Lacey. 2001. Change in ecosystem service values in the San Antonio area, Texas. *Ecological Economics* **39**:333–346.

Le Maitre, D. C., and P. J. O'Farrell. 2008. Social–ecological resilience in a dry environment: people and water resources in the Little Karoo. Pages 339–382 *in* M. Burns and A. Weaver, editors. *Exploring sustainability science—a Southern African perspective.* Sun Media, Stellenbosch, South Africa.

Le Maitre, D. C., S. J. Milton, C. Jarmain, C. A. Colvin, I. Saayman, and J. H. J. Vlok. 2007. Landscape-scale hydrology of the Little Karoo: linking ecosystems, ecosystem services and water resources. *Frontiers in Ecology and the Environment* **5**:261–270.

Levy, M., S. Babu, K. Hamilton, V. Rhoe, A. Catenazzi, M. Chen, W. V. Reid, D. Sengupta, C. Ximing, A. Balmford, and W. Bond. 2005. Ecosystem conditions and human well-being. Pages 125–164 *in* R. Hassan, R. J. Scholes, and N. Ash, editors. *Ecosystems and human well-being. Volume 1. Findings of the Conditions and Trends Working Group of the Millennium Ecosystem Assessment.* Island Press, Washington, D.C., USA.

Li, R.-Q., M. Dong, J.-Y. Cui, L.-L. Zhang, Q.-G. Cui, and W.-M. He. 2007. Quantification of the impact of land-use changes on ecosystem services:

a case study in Pingbian County, China. *Environmental Monitoring and Assessment* **128**:503–510.

Max-Neef, M. A. 2005. Foundations of transdisciplinarity. *Ecological Economics* **53**:5–16.

Mills, A. J., and R. M. Cowling. 2006. Rate of carbon sequestration at two thicket restoration sites in the Eastern Cape, South Africa. *Restoration Ecology* **14**:38–49.

Mills, A. J., R. M. Cowling, M. V. Fey, G. I. H. Kerley, J. S. Donaldson, R. G. Lechmere-Oertel, A. M. Sigwela, A. L. Skowno, and P. Rundel. 2005. Effects of goat pastoralism on ecosystem carbon storage in semiarid thicket, Eastern Cape, South Africa. *Austral Ecology* **30:**797–804.

Millennium Ecosystem Assessment (MA). 2003. *Ecosystems and human well-being: a framework for assessment.* Island Press, Washington, D.C., USA.

Millennium Ecosystem Assessment (MA). 2005. *Millennium ecosystem assessment synthesis report.* Island Press, Washington, D.C., USA.

Mitchell, C. A., A. L. Carew, and R. Clift. 2004. The role of the professional engineer and scientist in sustainable development. Pages 29–56 *in* A. Azapagig, S. Perdan, and R. Clift, editors. Sustainable development in practice: case studies for engineers and scientists. Wiley, Chichester, UK.

Mittermeier, R. A., M. Hoffmann, J. D. Pilgrim, T. B. Brooks, C. G. Mittermeier, J. L. Lamoreux, and G. Fonseca., editors. 2005. Hotspots revisited: earth's biologically richest and most endangered ecoregions. Cemex, Mexico City, Mexico.

O'Farrell, P. J., J. S. Donaldson, and M. T. Hoffman. 2007. The influence of ecosystem goods and services on livestock management practices on the Bokkeveld plateau, South Africa. *Agriculture, Ecosystem and Environment* **122**:312–324.

O'Farrell, P. J., D. C. Le Maitre, C. Gelderblom, D. Bonora, T. Hoffman and B. Reyers. 2008. Applying a resilience framework in the pursuit of sustainable land-use development in the Little Karoo, South Africa. Pages 383–430 *in* M. E. Burns, and A. v. B. Weaver, editors. *Exploring sustainability science—a Southern African perspective.* Sun Press, Stellenbosch, South Africa.

Pereira, H. M., B. Reyers, M. Watanabe, E. Bohensky, S. Foale, C. Palm, V. Espaldon, D. Armenteras, M. Tapia, A. Rincon, M. Lee, A. Patwardhan, and I. Gomes. 2005. Condition and trends of ecosystem services and biodiversity. Pages 87–117 *in* D. Capistrano, C. Samper, M. J. Lee, and C. Raudsepp-Hearne, editors. *Ecosystems and human well-being: multi scale assessments. Volume 4. Findings of the Sub-global Assessments Working Group of the Millennium Ecosystem Assessment.* Island Press, Washington, D.C., USA.

Pierce, S. M., R. M. Cowling, A. T. Knight, A. T. Lombard, M. Rouget, and T. Wolf. 2005. Systematic conservation assessment products for land use planning: interpretation for implementation. *Biological Conservation* **125**:441–548.

Prendergast, J. R., R. M. Quinn, J. H. Lawton, B. C. Eversham, and D. W. Gibbons. 1993. Rare species, the coincidence of diversity hot spots and conservation strategies. *Nature* **356**:335–337.

Priess J. A., M. Mimler, A. Klein, S. Schwarze, T. Tscharntke, and I. Steffan-Dewenter. 2007. Linking deforestation scenarios to pollination services and economic returns in coffee agroforestry systems. *Ecological Applications* **17**(2):407–417.

Rodríguez, J. P., T. D. Beard, Jr., E. M. Bennett, G. Cumming, S. Cork, J. Agard, A. P. Dobson, and G. D. Peterson. 2006. Trade-offs across space, time, and ecosystem services. *Ecology and Society* **11**(1): 28. [online] URL: http://www.ecologyandsociety.org/vol11/iss1/art28/.

Rouget, M., R. M. Cowling, J. H. J. Vlok, M. Thompson, and A. Balmford. 2006. Getting the biodiversity intactness index right: the importance of habitat degradation data. *Global Change Biology* **12**:2032–2036.

Ruhl, B., S. E. Kraft, and C. L. Lant. 2007. The law and policy of ecosystem services. Island Press, Washington, D.C., USA.

Safriel, U., Z. Adeel, D. Niemeijer, J. Puigdefabregas, R. White, R. Lal, M. Winslow, J. Ziedler, S. Prince, E. Archer, and C. King. 2005. Dryland systems. Pages 623–662 *in* R. Hassan, R. J. Scholes, and N. Ash, editors. *Ecosystems and human well-being. Volume 1. Findings of the Conditions and Trends Working Group of the*

Millennium Ecosystem Assessment. Island Press, Washington, D.C., USA.

Scholes, R. J., and R. Biggs. 2005. A biodiversity intactness index. *Nature* **434**:45–49.

Swinton, S. M., F. Lupi, G. P. Robertson, and S. K. Hamilton. 2007. Ecosystem services and agriculture: cultivating agricultural ecosystems for diverse benefits. *Ecological Economics* **64**(2):245–252.

Thompson, M., J. H. J. Vlok, M. Rouget, M. T. Hoffman, A. Balmford, and R. M. Cowling. 2009. Mapping land transformation in a heterogeneous environment: a rapid and cost effective approach for assessment and monitoring. *Journal of Environmental Management, in press*.

Turner, B.L. II, P. A. Matson, J. McCarthy, R. W. Corell, L. Christensen, N. Eckley, G. K. Hovelsrud-Broda, J. X. Kasperson, R. E. Kasperson, A. Luers, M. L. Martello, S. Mathiesen, R. Naylor, C. Polsky, A. Pulsipher, A. Schiller, H. Selink, and N. Tyler. 2003. Illustrating the coupled human–environment system for vulnerability analysis: three case studies. *Proceedings of the National Academy of Science*s **100**:8080–8085.

Turpie, J. K., C. Marais, and J. Blignaut. 2008. The working for water programme: evolution of a payments for ecosystem services mechanism that addresses both poverty and ecosystem service delivery in South Africa. *Ecological Economics* **65**:788–798.

van Jaarsveld, A. S., R. Biggs, R. J. Scholes, E. Bohensky, B. Reyers, T. Lynam, C. Musvoto, and C. Fabricius. 2005. Measuring conditions and trends in ecosystem services at multiple scales: the Southern African Millennium Ecosystem Assessment (SAfMA) experience. *Philosophical Transactions of the Royal Society B* **360**:425–441.

van Kerkhof, L., and Lebel, L. 2006. Linking knowledge and action for sustainable development. *Annual Review of Environment and Resources* **31**:445–477.

Viglizzo, F., and F. C. Frank. 2006. Land-use options for Del Plata Basin in South America: tradeoffs analysis based on ecosystem service provision. *Ecological Economics* **57**:140–151.

Vitousek, P. M., H. A. Mooney, J. Lubechenco, and J. M. Melillo. 1997. Human domination of earth’s ecosystems. *Science* **277**:494–499.

Vlok, J. H. J., R. M. Cowling, and T. Wolf. 2005. A vegetation map for the Little Karoo. Unpublished Maps and Report for a SKEP Project Supported by Grant No. 1064410304. Critical Ecosystem Partnership Fund, Cape Town, South Africa. [online] URL: http://bgis.sanbi.org/littlekaroo/index.asp.

Wiegand, T., S. J. Milton, and C. Wissel. 1995. A simulation model for a shrub ecosystem in the semi-arid Karoo, South Africa. *Ecology* **76**:2205–2211.

Yadav, V., and G. Malanson. 2008. Spatially explicit historical land use land cover and soil organic carbon transformations in Southern Illinois. *Agriculture, Ecosystems and Environment* **123**:280–292.

Zhao, B., U. Kreuter, B. Li, Z. Ma, J. Chen, and N. Nakagoshi. 2004. An ecosystem service value assessment of land-use change on Chongming Island, China. *Land Use Policy* **21**:139–148.

APPENDIX 1. Methods and data used to map ecosystem services.

Potential forage production
Carrying capacities for domestic stock, expressed as number of ha required per large stock unit (LSU), were determined for pristine examples of the 32 habitat types defined in Vlok et al. (2005). This service was mapped by overlaying the carrying capacity recommendation map of the Department of Agriculture (DA) with those of the habitat map prepared by Vlok et al. (2005) for the Little Karoo domain. It is important to note that not all habitat types of the Little Karoo are covered by the DA map; however it does provide clear recommendations for the habitat types with the highest (valley thicket with spekboom) and lowest (*Proteoid fynbos*) carrying capacity, as well as several other clear recommendations at other carrying capacities (e.g., for Apronveld, Gannaveld, and Sandolienveld). For habitat units not recognized by the DA map, carrying capacity recommendations for pristine examples of such types had to be interpolated. This was done by estimating the degree to which plants palatable to domestic stock would increase or decrease in the habitat type in relation to the DA recommendation for the most similar habitat type. These estimates were reviewed in terms of the range recommended by the DA, as well as by officers from the DA. We assigned a medium level of certainty to these reviewed and well understood data.

Potential carbon storage
Carbon storage refers to the number of tons of carbon locked up in the above and below ground biomass of plants; most of this carbon would be released if these intact ecosystems were transformed or degraded. In mapping this service, we (similar to Chan et al. 2006), focused on carbon storage rather than sequestration as an ecosystem service, mostly because of the data gaps and uncertainty in estimating sequestration. Most Little Karoo habitat types were assigned zero carbon storage values due to their arid, fire prone nature. For the remainder, carbon storage values were extracted for the habitat types of arid thicket with spekboom based on research on carbon storage in the region (Mills et al. 2005, Mills and Cowling 2006). Through a process of expert consultation, the more mesic thicket with spekboom types were assigned higher values based on higher predicted biomass. Similarly, arid thicket types without spekboom (*Portulacaria afra*) were assigned lower values owing to the large contribution of this species to carbon stocks (Mills et al. 2005). Three remaining habitat types (Randteveld, Gravel Apronveld, and Thicket Mosaics) were assigned small values to reflect the small amount of carbon they potentially store. The ecosystem service was mapped as tons of carbon stored per ha per habitat type. We assigned a high certainty to the carbon storage values of the arid thicket with spekboom type, and low certainties to the remaining values where scientific understanding is still in development.

Potential erosion control
In mapping this ecosystem service, we assessed the interaction between rainfall, soil depth and texture for each habitat type. This information was used to assign habitat types to classes of high, medium, and low erosion hazard. These classes were determined using the vegetation descriptions in Vlok et al. (2005) and through expert consultation. We identified high erosion hazard habitat types as all of those belonging to the aquatic source (streams and seepage areas) and drainage (river and floodplains) biomes, as well as the *Gannaveld* types which are located in valley bottoms and often form large open plains just above the river and floodplain habitat type. *Gannaveld* types have deep, fine-fractured soils very prone to erosion, with rainstorms transferring soils to the riverine and floodplain habitats causing declines in water quality and nutrient enrichment. These habitat types are associated with high runoff (high rainfall mountain catchment areas) and high run on areas (lowlands with vulnerable soils plus other functions (e.g. nutrient retention)) and are areas where the maintenance of pristine vegetation cover is essential. These areas form the focus of this study. Areas of medium hazard include the remaining mesic and montane habitat types, which are important for water run-off and drainage. We assigned a high certainty to these qualitative ranks based on a sound expert understanding of the service.

Potential water-flow regulation
In mapping this service, we used data on both water-flow regulation and water-quality regulation. The

former is a function of how much water infiltrates the soil, passes beyond the root zone, and recharges the groundwater stored in the catchment (Sandström 1998). Infiltration is primarily regulated by the texture of the soils (rapid in sandy soils and slow in clays) and inputs from the vegetation and fauna which maintain the soil porosity and protect it from the erosive forces of raindrops and unhindered surface run-off (Dean 1992, Bruijnzeel 2004, Ludwig et al. 1997). From the human use perspective, the most important component of the water flows is the sustained flows which meet needs in the dry season and also increase yields from storage dams. One measure of sustained flows is the river baseflow which is the main component of the flow during the dry season and is typically generated by groundwater discharge (Farvolden 1963). The most appropriate dataset for estimating these flows was gridded data on groundwater recharge extracted from the Department of Water Affairs and Forestry (DWAF 2005). This estimate combines data on rainfall, geology (lithology), and estimates of recharge (e.g., from chloride profiles) to provide a grid on recharge depth at a 1 km x 1 km resolution. These estimates take into account losses due to evaporation from the soil, interception, and transpiration of soil water by plants (i.e., green water), but not the losses during the groundwater discharge into rivers (e.g., through riparian vegetation).

In mapping the water-quality component of the service, we used data on the relationship between geology (primary lithology) and groundwater-quality (electrical conductivity) because high sodium chloride (salinity) concentrations make the water unfit for domestic use. Data on groundwater-quality were extracted from borehole water analyses stored in the Water Management System database of the Department of Water Affairs and Forestry. The results were summarized by the primary lithology taken from the 1:1 million geological data (Council for Geosciences 1997). Formations where the electrical conductivity exceeded the target water-quality range for acceptability for domestic water supplies (DWAF 1996) were used to identify and exclude areas where water-quality was deemed unacceptable for domestic consumption. We assigned a high certainty to these well understood and peer-reviewed data.

Potential tourism

Using ArcGIS 9.2 (ESRI 2008), we modelled a 10 km viewshed of the major tourist routes of the Little Karoo. The distance was determined based on visual assessments in the region. This viewshed was extracted and used as the ecosystem service of tourism. We assigned a medium level of certainty to these data due to our limited understanding of the full suite of drivers of tourism in the region.

LITERATURE CITED

Bruijnzeel, L. A. 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture, Ecosystems and Environment* **104**:185–228.

Chan, K. M. A., M. R. Shaw, D. R. Cameron, E. C. Underwood, and G. C. Daily. 2006. Conservation planning for ecosystem services. *PLoS Biology* **4** (11:e379). doi:10.1371/journal.pbio.0040379.

Council for Geosciences. 1997. 1:1 000 000 scale geological map of the Republic of South Africa and the Kingdoms of Lesotho and Swaziland. Council for Geoscience, Pretoria, South Africa.

Dean, W. R. J. 1992. Effects of animal activity on the absorption rate of soils in the southern Karoo, South Africa. *Journal of the Grassland Society of Southern Africa* **9**:178–180.

Department of Water Affairs and Forestry (DWAF). 1996. South African water quality guidelines: domestic water use. 2nd edition, volume 1. Department of Water Affairs and Forestry, Pretoria, South Africa.

Department of Water Affairs and Forestry(DWAF). 2005. Groundwater resource assessment, phase

II, methodology: groundwater-surface water interactions. Department of Water Affairs and Forestry, Pretoria, South Africa. [online] URL: http://www.dwaf.gov.za/ Geohydrology/gra2/3aEFinalReportA.pdf.

Environmental Systems Research Institute (ESRI). 2008. ArcGIS Desktop (ArcInfo) Software. ESRI, California, USA.

Farvolden, R. N. 1963. Geologic controls on ground-water storage and base flow. *Journal of Hydrology* **1**:219–249.

Ludwig, J. A., D. J. Tongway, D. O. Freudenberger, J.C. Noble, and K. C. Hodgkinson, editors. 1997. Landscape ecology, function and management: principles from Australia's rangelands. CSIRO, Melbourne, Australia.

Mills, A. J., and R. M. Cowling. 2006. Rate of carbon sequestration at two thicket restoration sites in the Eastern Cape, South Africa. *Restoration Ecology***14**:38–49.

Mills, A. J., R. M. Cowling, M. V. Fey, G. I. H. Kerley, J. S. Donaldson, R. G. Lechmere-Oertel, A. M. Sigwela, A. L. Skowno, and P. Rundel. 2005. Effects of goat pastoralism on ecosystem carbon storage in semiarid thicket, Eastern Cape, South Africa. *Austral Ecology* **30**:797–804.

Sandström, K. 1998. Can forests 'provide' water: widespread myth or scientific reality? *Ambio* **27**:132–138.

Vlok, J. H. J., R. M. Cowling, and T. Wolf. 2005. A vegetation map for the Little Karoo. Unpublished Maps and Report for a SKEP project
Supported by Grant No 1064410304. Critical Ecosystem Partnership Fund. Cape Town, South Africa. [online] URL: http://bgis.sanbi.org/littlekaroo/index.asp.

APPENDIX 2. Ecosystem service values per habitat type for each state of land-cover.

Habitat type	Forage production (ha/LSU)			Carbon storage (tons/ha)		
	Pristine	Moderately degraded	Severely degraded	Pristine	Moderately degraded	Severely degraded
Freshwater stream & seepage areas	140	180	210	0	0	0
River & floodplain	60	80	120	0	0	0
Apronveld	54	70	90	0	0	0
Arid Proteoid	140	180	210	0	0	0
Arid Renosterveld	108	140	160	0	0	0
Arid Renosterveld Mosaics	72	95	110	0	0	0
Arid Thicket Mosaics	75	90	100	120	100	80
Arid Thicket with Spekboom	66	85	100	200	150	100
Arid Thicket with Spekboom Mosaics	70	90	100	200	150	100
Asbosveld	72	90	110	0	0	0
Asteraceous	108	120	160	0	0	0
Ericaceous	140	180	210	0	0	0
Gannaveld	60	85	110	0	0	0
Grassy	60	90	105	0	0	0
Gravel Apronveld	72	95	105	20	10	5
Kalkveld	54	80	95	0	0	0
Mesic Proteoid	140	180	210	0	0	0
Mesic Renosterveld	60	85	110	0	0	0
Mesic Renosterveld Mosaics	60	85	110	0	0	0
Quartz Apronveld	65	80	90	0	0	0
Quartz Asbosveld	72	90	110	0	0	0
Quartz Gannaveld	60	85	110	0	0	0
Randteveld	80	95	120	30	15	5

(con'd)

Restioid	108	120	160	0	0	0
Sandolien	72	95	120	0	0	0
Scholtzbosveld	72	95	110	0	0	0
Subalpine	140	180	210	0	0	0
Thicket Mosaics	72	90	110	50	40	30
Valley Thicket Mosaics	60	80	100	150	120	100
Valley Thicket with Spekboom	48	70	80	250	180	120
Valley Thicket with Spekboom Mosaics	55	75	90	250	180	120
Waboomveld	60	90	105	0	0	0

Note: Converted areas are assumed to produce none of the ecosystem service and thus the fourth class of land-cover, transformed, is not shown here.

APPENDIX 3. Reduction in water-flow regulation for each biome per land-cover category.

Biome	% Reductions in groundwater recharge		
	Pristine	Moderately degraded	Severely degraded
Fynbos	0	0	0
Renosterveld	0	10	50
Succulent Karoo	0	10	50
Subtropical Thicket	0	10	50
Aquatic (Drain & Source)	0	10	50

Note: Converted areas are assumed to produce none of the ecosystem service and thus the fourth class of land-cover, transformed, is not shown here.

Designing an Integrated Global Monitoring System for Drylands

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Abstract – Drylands occupy between 30 and 40% of the world's land surface, and host between 1 and 2 billion people, depending on how they are delimited. The development of drylands is hampered by a number of factors including severe natural and social environment constraints, but these regions also offer unique features and opportunities. The recent Drylands Development Paradigm (DDP) provides an intellectual context to re-think how humanity interacts with these harsh and fragile environments. Progress in understanding the key processes, in selecting appropriate policies and actions, as well as in evaluating their effectiveness has hitherto been hampered by the lack of a systematic, comprehensive, integrated observing system to document the state and evolution of drylands. This paper outlines some of the requirements for a Global Drylands Observing System (GDOS) and suggests how it could complement existing efforts in the fields of climate change and environmental degradation.

Keywords: Drylands, Global Observing Systems, DDP, UNCCD, GCOS, GEO BON, desertification, remote sensing.

1. INTRODUCTION

Drylands tend to be very large, remote, inaccessible areas characterized by limited soil moisture and fresh water availability, low plant productivity, relatively sparse human populations and lack of infrastructures (e.g., for transportation and energy distribution). These environments, fragile in some respects but very resilient in others, have nevertheless hosted considerable numbers of (often nomadic) communities through many millennia, in traditional socio-economic structures adapted to the rigor and inherent variability of drylands. Significant changes in the last two centuries include colonization by settlers from very different environments (mostly Europe), the discovery and exploitation of huge underground mineral resources, irrigation of large areas without sufficient concern for the long-term sustainability of such operations, the progressive integration into the global economy, and reduced mortality in indigenous populations. These, in turn, have resulted in sedentarization, population increase and emigration, overgrazing or land abandonment, soil erosion and salinization, higher dependency on external subsidies, and the progressive loss of traditional values.

The slow but persistent desertification of arid and semi-arid lands has been a serious concern for decades, from the UN Conference on Desertification (UNCOD) in 1977 in Nairobi, Kenya to the adoption of the UN Convention to Combat Desertification (UNCCD) in 1992 at the Earth Summit in Rio de Janeiro (See http://www.unccd.int/). Yet progress has been slow and often inadequate in resolving these issues, despite considerable investments in aid programs. This finding, in turn, has stimulated a change in the conceptual framework in which these problems are addressed. The Drylands Development Paradigm (DDP) (Reynolds et al., 2007) outlines a new approach to promote the sustainable development of these regions.

2. WHY DO WE NEED AN OBSERVING SYSTEM?

Sound environmental policy should be based on sufficient and accurate information about the nature, scope, extent of and trends in the problems at hand, as the basis for an adaptive learning approach to improving outcomes. This implies an adequate knowledge of the state of the system and an understanding of the key processes that control its evolution. Reliable information on the risks and costs associated with mitigation and adaptation measures is needed to choose between alternative options, especially when resources are limited. Assessing the cost effectiveness of policies and actions, and possibly reorienting these to improve efficiency or address emerging issues also requires continued monitoring of how the environment is changing, as well as of the consequences of these changes on social, political and economic systems.

Useful lessons about the need for, role and impact of an observing system can be learned from similar experiences in other fields. The atmospheric community is arguably the best organized in this area, in large part because of the long history of measurements and synoptic analyses, as well as lasting collaborations to detect the genesis and predict the track of storms and other severe weather events. Most countries maintain extensive networks of observing stations in support of research, weather forecast and climate assessments, as well as a range of applications including the day-to-day management of the agriculture, transport, public health and energy sectors, to mention but a few. When the possibility of significant future climate changes and the likelihood of major impacts became generally clear, governments adopted the UN Framework Convention on Climate Change (UNFCCC) at the Rio de Janeiro Earth Summit in 1992 (See http://unfccc.int/2860.php). A separate institution, the Global Climate Observing System (GCOS) was created, also in 1992 (See http://www.wmo.int/pages/prog/gcos/index.php), to ensure that all actors requiring climate information (from research to forecasting and from impacts to mitigation and adaptation) would have access to adequate information on the state and evolution of the climate system.

The UN Convention on Biodiversity (UNCBD) was also adopted at this Earth Summit (See http://www.cbd.int/), and that community has recently organized itself into a 'new global partnership to help collect, manage, analyze, and report data relating to the status of the world's biodiversity' (Scholes et al., 2008). Their GEO BON network has been conceived from the

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start as a component of the Group of Earth Observations (GEO) (See http://www.earthobservations.org/cop_bi_geobon.shtml), an institution established in 2002 at the World Summit on Sustainable Development to coordinate international efforts to build a Global Earth Observation System of Systems (GEOSS) (See http://www.earthobservations.org/). Subsequently, the GCOS has also become the climate component of the GEOSS.
The UNCCD was the third major convention adopted in Rio, and the only one that does not have a dedicated observing system, or even an explicit strategy to create such a system. This is not to say that no observations are made in drylands: the problem is that the measurements are uncoordinated, neither integrated across scales nor standardized, and often inaccessible. They do not provide a compelling view of the problems of drylands, nor do they systematically support the planning, implementation and assessment of effective actions. For instance, in 2005, the Millennium Ecosystem Assessment (See http://www.millenniumassessment.org/en/index.aspx) could only conclude that 10 to 20% of drylands were desertified, and this only with medium certainty (MEA 2005).

The extent of existing land degradation, cumulated over decades of inappropriate or insufficient management, the severity of the consequences of the progressive reduction of ecosystem services for the local populations, the urgency resulting from on-going and expected climate changes and their impacts on drylands, and the implications of these perturbations for the rest of the world underscore the pressing necessity to address these problems promptly. The time is ripe to reinvigorate efforts in this direction: new findings in physical, biological and social sciences, as well as modern technologies of remote sensing, data processing and communication converge to provide an intellectual and practical framework in which complex systems such as drylands can be efficiently understood and simulated, meaningful measurements and observations can be obtained and analyzed, and local knowledge and traditional expertise can be integrated into a broad panoply of concepts, tools and techniques to promote the sustainable development of drylands. Organizing and coordinating efforts to systematically monitor key aspects of drylands will go a long way towards ensuring that these efforts are sound, appropriate and effective.

3. ARE EXISTING SYSTEMS INADEQUATE?

As noted above, the international community has already setup a number of observing systems to closely monitor the various components of the global environment. In addition to the GCOS (which hosts the Terrestrial Observation Panel for Climate, TOPC) and the GEOSS already mentioned, the Global Terrestrial Observing System (GTOS) was created in 1995 and hosted by the Food and Agricultural Organization (FAO), to 'facilitate access to information on terrestrial ecosystems so that researchers and policy makers can detect and manage global and regional environmental change'. However, none of these existing systems *focuses* on the problems of drylands. Drylands share some of the same general observational requirements with other regions, but also have specific needs that are not automatically fulfilled by systems that largely evolved in wetter, more developed environments. These specific needs arise from the nature of drylands as water limited, variable, resource scarce, remote systems with strong direct linkages between social and environmental outcomes (Reynolds, et al 2007), and include the following requirements:

- Water inaccessibility constitutes the essential defining characteristics of drylands. Much of the water required by human communities in drylands (especially for domestic use and livestock watering) originates predominantly from groundwater, a resource that is not well-observed by river-oriented hydrological networks, and remains largely invisible from space.
- Water in drylands may not be lacking in absolute terms: hot air can hold much more water vapor than cold air; and salt water is often abundant. What is frequently missing in these regions is a mechanism (e.g., convection) to cool the air to the point where water vapor condenses and become usable. Some plants (in particular lichens, which dominate hyperarid environments) have evolved to capture fog droplets or dew. Thus, while characterizing the water cycle is critical in all environments, specific or dedicated measurements are needed in drylands to provide relevant information to understand natural processes or promote sustainable development.
- The high spatial and temporal variability of climatic variables in drylands is well known. Traditional dryland societies have adapted to these constraints, at least as long as variability remains within some 'expected' range of variation. Drylands herders and farmers can survive, albeit at a high cost, vagaries such as a string of consecutive poor rainy seasons, for instance. Recently created or transplanted societies lack this capacity. Long-term trends or extended periods of unavailability of essential resources that exceed the resilience capacity of the concerned societies generate the most serious problems. Hence, it is critical that a Drylands Observing System pays much more attention to the slowly evolving variables than to their high frequency components.
- A direct (typically but not necessarily linear) relation usually exists between the availability of a resource and the output of a system, be it agricultural or socio-economic. Within a certain range of input or constraints, deficits or excesses result in corresponding changes in productivity and the system recovers from (or takes advantages of) the situation: these relations are called 'elastic', because the overall long-term capacity to deliver products and services is not affected by such events. However, when the changes in the system exceed a threshold, it may not able to recover, even if the pressures are alleviated, and the system evolves towards another, often less productive, state. Such a system will not of its own accord return to its previous state, at least not in a reasonable period. These systems exhibit 'inelastic' responses to stress, or a form of hysteresis. For instance, soil loss occurs naturally on an ongoing basis at a low rate, more-or-less balanced by soil genesis. However, loss of vegetative cover can result in much more rapid soil erosion, affecting its ability to host useful plant life. It is essential to define and monitor these thresholds and characterize the traps (undesirable states) in which dryland ecosystems may fall as a result of cumulative stresses or exceptional, extreme events.

- Lands that are not water-limited can usually be used productively in a wide range of alternative ways, including for agriculture, forestry, industry, transportation, commercial activities or urban development. This is not often the case in drylands, where the harsh physical environment restricts the set of sustainable lifestyles and economic activities. As a result, individuals and societies are much more intricately linked to their environment and constrained in their options. Social sciences (encompassing the whole gamut of fields from individual psychology to social structure, from land ownership to economic organization and from cultural settings to governance practices) play an even more important role in determining the future of drylands than in other environments. It would thus be inconceivable to setup a Drylands Observing System that does not include a range of social, economic and political variables. None of these are (currently) part of any of the existing global observation systems.

Beyond these specific needs, what is often missing in dryland observations is an integrated, coherent approach to collecting the data, analyzing it and delivering it as information that is relevant not only for managing the local environment but also to take actions at the national or international levels. A Drylands Observing System cannot by itself ensure the emergence of such a rational approach everywhere, or guarantee the successful and sustainable development in drylands. But neither of those objectives is likely without one. A Global Drylands Observation System would contribute by promoting objective, repeatable and harmonized measurements, facilitating the acquisition, archiving and distribution of relevant information, supporting research and development, and assessing impacts or quantifying the efficiency and effectiveness of adopted policies and measures.

4. TOWARDS AN INTEGRATED GDOS

These considerations, together with the findings of the Millennium Ecosystem Assessment and the generic framework provided by the Drylands Development Paradigm mentioned earlier, suggest that a Global Drylands Observing System (GDOS) would have the following characteristics (Verstraete et al., 2008, 2009):

- Focus primarily on slow variables and their thresholds, rather than on the intrinsic high-frequency variability of the system.
- Cover the range of relevant ecosystem services, such as fodder, fuel and crop production, water yield, and biodiversity habitat provision.
- Include both human and environmental dimensions, paying special attention to generating measurements and observations that can be 'co-registered' on compatible scales and resolutions.
- Address the need to collect data and deliver information at a range of scales and resolutions and for a variety of users.
- Include measures of local environmental knowledge and its evolution.
- Support adaptive processes for triggering action as a result of monitoring feedback (Lynam and Stafford Smith, 2004), including an ability to update the monitoring system itself.
- Build a nested approach which empowers the use of in-country data collection but helps to coordinate, interpret and quality control these data across national boundaries, and integrate it with data (particularly remote sensing and social data) that can be collected at global scales with local resolution.

In this context, it will be profitable to learn from the experience of existing monitoring systems to trace a path towards implementing such a system. For instance, the following steps have been found to be very valuable in the case of GCOS and could guide the establishment of a GDOS:

- Harmonize overall requirements with the UNCCD and its Committee on Science and Technology (CST), and regularly report on progress.
- Review the state of existing national observational networks and institutions, and evaluate their adequacy to address issues in drylands, taking into account the contributions of existing global observation systems (GCOS, 2003).
- Draft a strategy and an implementation plan, gathering constructive criticisms and suggestions from the scientific community along the way (GCOS, 2004).
- Establish priority lists of key variables, both within the natural and human sciences that should be measured to address the range of issues typically encountered in drylands.
- For each of these essential variables, agree on units or measurement, acceptable measurement protocols and minimum required accuracy, as well as propose calibration, validation and benchmarking exercises to establish the reliability of the information.
- Setup archives and observation networks, paying special attention to formats and interoperability, but also ensuring effective access to data, especially for researchers and developing countries (intellectual right issues and data policies).
- Target specific efforts to recover and preserve historical records that may otherwise disappear due to ineffective or inexistent preservation, or remain inaccessible.
- Coordinate with existing global observation systems (e.g., GCOS, GTOS) and the GEOSS to setup institutional arrangements, clarify the respective roles and contributions of each system, and facilitate communications.
- Liaise with the Committee on Earth Observation Satellites (CEOS), Space Agencies and other Data Providers to ensure access to existing databases as well as to prepare for future missions.

Once operational, such a GDOS would obviously support the implementation of the National Plans of Action to Combat Desertification (NPACD), as well as their coordination at the international level (e.g., through UNCCD or UNEP). It should be designed and implemented with the support and ownership of a sufficient number of nations subject to desertification so that a global system can be activated, but without requiring full participation by every country.

5. CONCLUSIONS

Collecting and analyzing data, and even distributing indicators, products, assessments and other information on the state and evolution of drylands are not sufficient to effectively address the environmental and human challenges facing these regions. However, the currently limited access to partial and disparate data and the lack of key information on the processes at hand, on the current and expected impacts, or on the remedial options and associate costs have definitely hindered progress on a range of scales, from the local management of natural resources to the international coordination of the combat against desertification.

A Global Drylands Observing System would not only provide a coherent, integrated solution to these problems but also support concerted efforts by the scientific community to better understand the processes at work and predict the risks and likely evolution of drylands. Historically, in all fields of science, expanded measurements and improved observations, combined with innovative thinking and paradigm changes, have resulted in major advances in understanding and therefore in the effectiveness of solutions. A comprehensive GDOS would also stimulate truly interdisciplinary research and foster investigations of complex issues such as the relations between soil erosion, dust mobilization and health, or between overgrazing, land ownership, population emigration and international security.

REFERENCES

GCOS, "Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC", GCOS Secretariat, Report No. 82, Geneva, Switzerland, April 2003, http://www.wmo.int/pages/prog/gcos/Publications/gcos-82_2AR.pdf.

GCOS, "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC," GCOS Secretariat, Report No. 92, Geneva, Switzerland, October 2004, http://www.wmo.int/pages/prog/gcos/Publications/gcos-92_GIP.pdf.

Lynam, T. and M. Stafford Smith, "Monitoring in a complex world – seeking slow variables, a scaled focus, and speedier learning," *African Journal of Range & Forage Science*, **21**, 69–78, 2004.

Millennium Ecosystem Assessment, Ecosystems and Human Well-Being: Desertification Synthesis, 1995, http://www.millenniumassessment.org/documents/document.355.aspx.pdf.

Reynolds, J. F., D. M. Stafford Smith, E. F. Lambin, B. L. Turner II, M Mortimore, S. P. J. Batterbury, T. E. Downing, H. Dowlatabadi, R. J. Fernandez, J. E. Herrick, E. Huber-Sannwald, H. Jiang, R. Leemans, T. Lynam, F T. Maestre, M. Ayarza and Brian Walker, "Global Desertification: Building a Science for Dryland Development," *Science*, Vol. **316**, 847–851, 11 May 2007, doi:10.1126/science.1131634.

Scholes, R. J., G. M. Mace, W. Turner, G. N. Geller, N. Jürgens, A. Larigauderie, D. Muchoney, B. A. Walther, H. A. Mooney, "Toward a Global Biodiversity Observing System," *Science*, Vol. **321**, 1044-1045, 22 August 2008, doi:10.1126/science.1162055.

United Nations Conference On Desertification *Desertification: Its Causes and Consequences*, Pergamon Press, 448 p., 1977, ISBN: 0-08-022033-1.

Verstraete, M. M., A. B. Brink, R. J. Scholes, M. Beniston, M. Stafford Smith, "Climate change and desertification: Where do we stand, where should we go?," *Global and Planetary Change*, Vol. **64**, 105-110, December 2008, doi:10.1016/j.gloplacha.2008.09.003

Verstraete, M. M., R. J. Scholes and M. Stafford Smith, "Climate and desertification: looking at an old problem through new lenses," *Frontiers in Ecology and the Environment*, Vol. **7**, 2009, doi:10.1890/080119.

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Predicting the deforestation-trend under different carbon-prices

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Abstract

Background: Global carbon stocks in forest biomass are decreasing by 1.1 Gt of carbon annually, owing to continued deforestation and forest degradation. Deforestation emissions are partly offset by forest expansion and increases in growing stock primarily in the extra-tropical north. Innovative financial mechanisms would be required to help reducing deforestation. Using a spatially explicit integrated biophysical and socio-economic land use model we estimated the impact of carbon price incentive schemes and payment modalities on deforestation. One payment modality is adding costs for carbon emission, the other is to pay incentives for keeping the forest carbon stock intact.

Results: Baseline scenario calculations show that close to 200 mil ha or around 5% of todays forest area will be lost between 2006 and 2025, resulting in a release of additional 17.5 GtC. Today's forest cover will shrink by around 500 million hectares, which is 1/8 of the current forest cover, within the next 100 years. The accumulated carbon release during the next 100 years amounts to 45 GtC, which is 15% of the total carbon stored in forests today. Incentives of 6 US$/tC for vulnerable standing biomass payed every 5 year will bring deforestation down by 50%. This will cause costs of 34 billion US$/year. On the other hand a carbon tax of 12 $/tC harvested forest biomass will also cut deforestation by half. The tax income will, if enforced, decrease from 6 billion US$ in 2005 to 4.3 billion US$ in 2025 and 0.7 billion US$ in 2100 due to decreasing deforestation speed.

Conclusion: Avoiding deforestation requires financial mechanisms that make retention of forests economically competitive with the currently often preferred option to seek profits from other land uses. Incentive payments need to be at a very high level to be effective against deforestation. Taxes on the other hand will extract budgetary revenues from the regions which are already poor. A combination of incentives and taxes could turn out to be a viable solution for this problem. Increasing the value of forest land and thereby make it less easily prone to deforestation would act as a strong incentive to increase productivity of agricultural and fuelwood production, which could be supported by revenues generated by the deforestation tax.

Background

Deforestation is considered the second largest source of greenhouse gas (GHG) emissions amounting to an estimated 2 gigatonnes of carbon (GtC) per annum over the last decade [1]. It is a persistent problem. The UN Food and Agriculture Organization, in its recently released most comprehensive assessment of forests ever, puts deforestation at about 12.9 mil. ha per year [2]. At the same time, forest planting, landscape restoration and natural expansion of forests reduce the net loss of forest area. Net change in forest area in the period 2000–2005 is estimated at -7.3 million hectares per year [2]. This reduces the annual GHG emissions to an estimated 1.1 GtC. In comparison, 7.3 GtC were emitted in 2003 by using fossil energy sources [3].

Deforestation has been difficult to tackle by governments, as its drivers are complex and many land uses yield higher revenues than those from forested land. Some see climate policy as a new opportunity to effectively reduce a major source of greenhouse gases and biodiversity loss as well as to increase incomes of many people in rural areas whose livelihood depends on forests. The implementation of measures avoiding deforestation would require innovative financial mechanisms in the context of global climate policies. In this paper we study the potential magnitude of effects of different financial mechanisms to help reduce deforestation, using a modeling approach.

To estimate the impact of financial incentives, to reduce deforestation and assuming profit maximizing behavior, we calculate differences in net present value of different land uses using a spatially explicit integrated biophysical and socio-economic land use model. Key model parameters, such as agricultural land use and production, population growth, deforestation and forest product consumption rates were calibrated against historical rates. Land use changes are simulated in the model as a decision based on a difference between net present value of income from production on agricultural land versus net present value of income from forest products. Assuming fixed technology, the model calculates for each 0.5° grid cell the net present value difference between agricultural and forest land-uses in one-year time steps. When carbon market prices, transferred through a financial mechanism, balance out differences between the net present value of agricultural land and forest-related income, it is assumed, consistent with profit maximising behavior, that deforestation is avoided.

The net present value difference of forest versus other land uses can be balanced out through two mechanisms. One is to reduce the difference by adding costs to conversion through taxing emissions from deforestation, e. g. through a land clearance tax and wood sales taxes. The other is to enhance the value of the existing forest by financial support when keeping the forest carbon stock, to be paid in certain time intervals. In both cases the value of forest carbon stock would be pegged to carbon market prices. The modeling results for different hypothetical tax or subsidy levels show the potential magnitude of avoided deforestation through financial incentive or disincentive mechanisms. The model results are annual, spatially explicit estimates of the forest area and biomass development from 2000 to 2100, with particular focus on the period 2006 to 2025.

Results and discussion

Baseline deforestation 2000–2100 and effects of financial mechanisms aiming at cutting emissions in half

Baseline scenario calculations (i.e. a carbon price of 0 US$/tC is assumed) show that close to 200 mil ha or around 5% of todays forest area will be lost between 2006 and 2025, resulting in a release of additional 17.5 GtC to the atmospheric carbon pool. The baseline deforestation speed is decreasing over time, which is caused by a decreasing forest area in regions with hight deforestation pressure. In the year 2025 the annual deforested area decreases to 8.2 million hectares, compared to 12.9 million hectares in 2005. By the year 2100 deforestation rates decline to some 1.1 million hectares. According to the base line scenario, today's forest cover will shrink by around 500 million hectares or by more than 1/8 within the next 100 years (figure 1).

Carbon emissions from deforestation in 2005 is 1.1 GtC/year and decreases to 0.68 GtC/year in 2025 and further

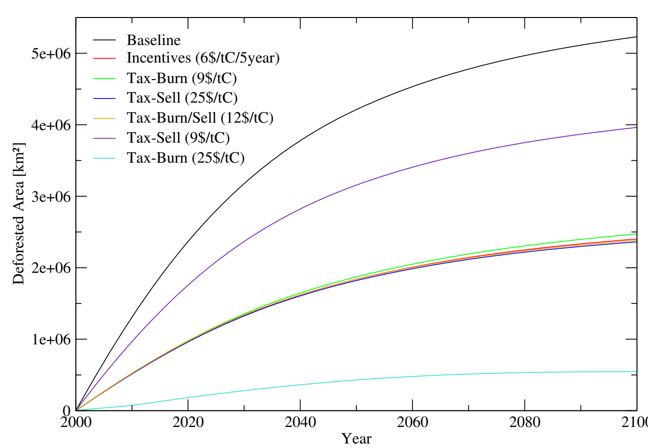

Figure 1

Deforested Area until 2100. Deforested Area under alternative assumptions. *Incentives*... Periodic payments for standing biomass, *Tax*... Payments for harvesting wood, *Burn*... felled wood is burned immediately, *Sell*... harvested wood is soled, *Burn/Sell*... share of the wood will be burned the other part soled.

to 0.09 GtC/year in 2100. The accumulated carbon release during the next 100 years amounts to 45 GtC which is 15% of the total carbon stored in forests today. To bring deforestation down by 50%, incentives of 6 US$/tC/5 year or a land clearance tax of between 9 US$/tC and 25 US$/tC would be necessary, depending whether the harvested wood is burned on the spot (e. g. slash-and-burn agriculture) or sold. In the latter case, a higher carbon tax of up to 25 US$/tC is necessary to effectively reduce incentives to deforest, to a degree that cuts overall global deforestation by 50%. If the wood is further used and converted into products, only 18% of the biomass could be saved by a carbon price of 9 US$/tC, caused by the compensating effect of an income by selling wood and a longer time-period for releasing carbon. On the other hand, if the carbon price is 25$/tC and the wood is assumed to be slash burned, the reduction of deforestation calculated to be 91% (figure 1 and 2). On a first sight it seems, that incentive payments might be more effective, than taxation. However, incentives payment contracts have to be renewed every 5 year for the actual standing biomass and the change of biomass has to be known to detect a breach of the contract, while a deforestation tax will be payed once for the harvested biomass once detected by targeted earth observation systems (see figure 3 and 4). In the latter, transactions costs for implementing avoided deforestation are small.

The assumption, that either only slash burn or all wood will be sold is unrealistic. Thus, a scenario where Latin America has 90% slash burn and 10% selling, Africa 50% slash burned and 50% selling and in the remaining area 10% slash burned and 90% selling, was examined. Under such scenario assumptions a carbon tax of 12 $/tC will cut deforestation in half. Also the assumption, that a carbon price will stay constant over time may not be close to reality but it can be used to see the long-term influence of a given carbon price.

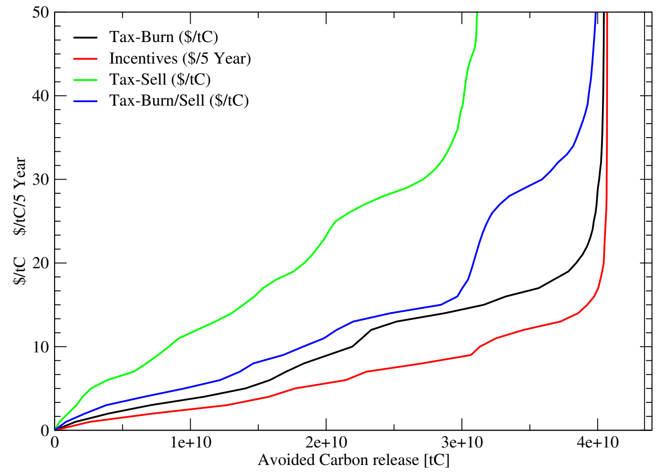

Figure 3
Avoided Carbon releases under different Carbon prices during the next 100 years. *Incentives*... Periodic payments for standing biomass, *Tax*... Payments for harvesting wood, *Burn*... felled wood is burned immediately, *Sell*... harvested wood is soled, *Burn/Sell*... share of the wood will be burned the other part soled.

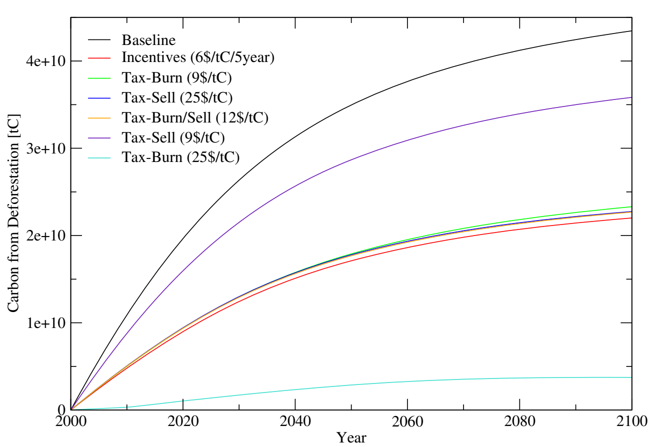

Figure 2
Released Carbon from Deforestation until 2100. Released carbon from deforestation under alternative assumptions. *Incentives*... Periodic payments for standing biomass, *Tax*... Payments for harvesting wood, *Burn*... felled wood is burned immediately, *Sell*... harvested wood is soled, *Burn/Sell*... share of the wood will be burned the other part soled.

We differentiate between the following cases:

Baseline: Introducing no carbon price.

Incentives: Introducing a carbon price which will be payed periodic for the carbon stored in the standing forest biomass.

All: Payments are done, without considering the effectiveness of the payment, in all regions.

Region: Payments are done in regions where the payments protect forest against deforestation.

Affected: Payments are done for forests where the payments protect them against deforestation.

Tax: Introducing a carbon price which has to be paid for releasing the stored carbon to the atmosphere.

Burn: All wood will be burned immediately.

Sell: All harvested wood will be sold.

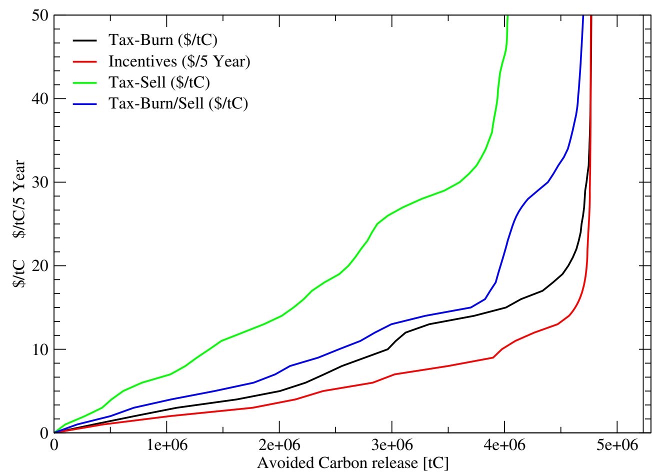

Figure 4
Saved Forest Area under different Carbon prices during the next 100 years. *Incentives*... Periodic payments for standing biomass, *Tax*... Payments for harvesting wood, *Burn*... felled wood is burned immediately, *Sell*... harvested wood is soled, *Burn/Sell*... share of the wood will be burned the other part soled.

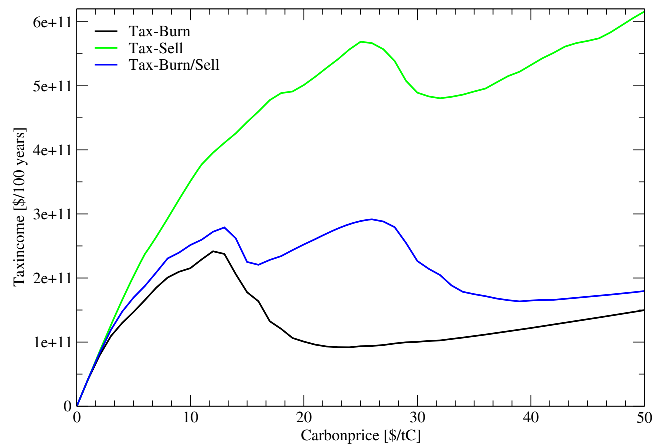

Figure 5
Income under different Carbon Prices. *Tax*... Payments for harvesting wood, *Burn*... felled wood is burned immediately, *Sell*... harvested wood is soled, *Burn/Sell*... share of the wood will be burned the other part soled.

Burn/Sell: A share of the wood will be burned and the other part sold.

Costs and revenues under different carbon prices

The effectiveness of introducing a carbon price to influence deforestation decisions depends largely on the levels set for carbon prices, apart from considerations of political feasibility and implementability. Low prices have little impact on deforestation rates. During the 21st century carbon tax schemes of 9 US$/tC for slash burn and 25 US$/tC for situations when removed wood enters a harvested wood products pool (HWP) would generate some 2 to 5.7 billion US$/year respectively when emissions from deforestation are to be cut in half. For the variant of 12 US$/tC, with regionally differentiated slash burn and HWP assumptions, the average annual income for the next 100 years are calculated to be around 2.7 billion US$. These tax revenues decrease dramatically over time mainly due to the declining baseline deforestation rate. Tax revenues are computed to be 6 billion US$ in 2005, 4.3 billion US$ in 2025 and 0.7 billion US$ in 2100. This indicates the magnitudes and their temporal change of funds generated from a deforestation tax scheme aiming at a 50% emission reduction (figure 5 and 7).

In the alternative incentive scheme, the amount of funds necessary, is depending on the strategy of payments, either increasing, staying constant or decreasing over time. If incentives are paid only for those forest areas that are about to be deforested, and with a global target of cutting deforestation by 50%, a minimum payment of 6 US$/tC/5 year or 0.24 billion US$ in 2006 would be required. This amount rises to some 1.2 billion US$ in 2010, 4.1 billion US$ in 2025 and 10 billion US$ in 2100 caused by the increasing area of saved forest area. As precise information of forests about to be deforested is absent, incentive payment schemes would have to focus on regions under deforestation pressure. Given that incentives are only spent on regions of 0.5° × 0.5° where they can effectively reduce deforestation in an amount that they will balance out the income difference between forests and alternative land use up the 6 US$/tC/5 year, this would come at a cost of 34 billion US$/year (figure 6 and 8). It should be noted that the tax applies only on places currently deforested while the subsidy applies to larger areas depending on how far it is in practice possible to restrict the subsidy to vulnerable areas. All figures above are intentionally free of transaction costs. Transaction costs would inter alia include expenditure for protecting the forests against illegal logging by force and expenditures monitoring small scale forest degregation. Governance issues such as corruption and risk adjustment, depending on the country are, however, considered in the analysis to the extent possible.

Regional effects of carbon prices on deforestation

Sources of deforestation in the model are expansion of agriculture and buildup areas as well as from unsustainable timber harvesting operations impairing sufficient reforestation. Deforestation results from many pressures, both local and international. While the more direct causes are rather well established as being agricultural expansion, infrastructure extension and wood extraction, indirect drivers of deforestation are made up of a complex web of

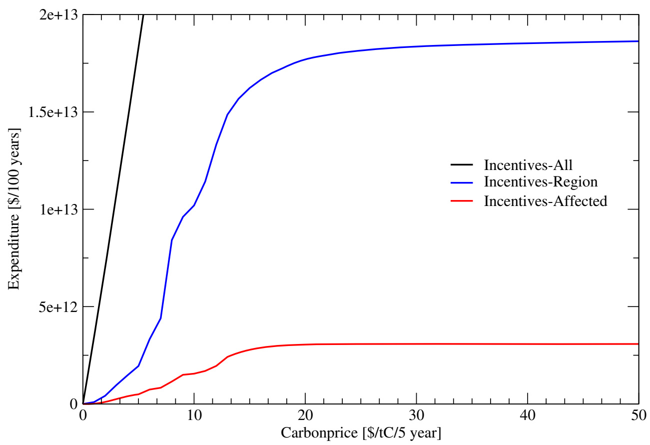

Figure 6
Expenditure under different Carbon Prices. *Incentives*... Periodic payments for standing biomass, *All*... Payments are done, without considering the effectiveness of the payment, in all regions, *Region*... Payments are done in regions where the payments protect forest against deforestation, *Affected*... Payments are done for forests where the payments protect them against deforestation.

interlinked and place-specific factors. There is large spatially differentiated heterogeneity of deforestation pressures. Within a forest-agriculture mosaic, forests are under high deforestation pressure unless they are on sites which are less suitable for agriculture (swamp, slope, altitude). Closed forests at the frontier to agriculture land are also under a high deforestation pressure while forest beyond

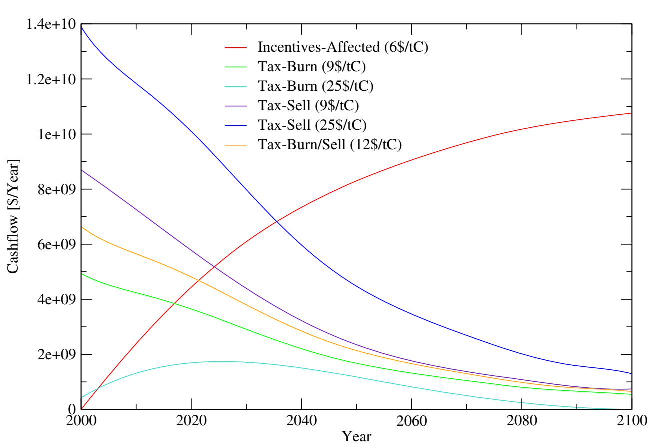

Figure 7
Cash flow until 2100 for different Carbon Prices. *Incentives*... Periodic payments for standing biomass, *Tax*... Payments for harvesting wood, *Affected*... Payments are done for forests where the payments protect them against deforestation, *Burn*... felled wood is burned immediately, *Sell*... harvested wood is soled, *Burn/Sell*... share of the wood will be burned the other part soled.

this frontier are under low pressure as long as they are badly attainable. The model was build to capture such heterogeneity in deforestation pressures.

Figure 9 shows that the model predicts deforestation to continue at the frontier to agricultural land and in areas which are easly accessible. Trans-frontier forests are also predicted to be deforested due to their relative accessibility and agricultural suitablility. Forests in mosaic lands continue to be under strong pressure. Figure 10 illustrates the geography of carbon saved at a carbon tax of 12 US$/tC compared to biomass lost through deforestation. Under this scenario deforestation is maily occurring in clusters, which are sometimes surrounded by forests (e.g. Central Africa) or are concentrated along a line (Amazon). The geography of the remaining deforestation pattern indicates that large areas are prevented from deforestation at the frontier by the 12 US$/tC tax. The remaining emissions from deforestation are explained mainly by their accessibility and favourable agricultural suitability.

Conclusion

Avoiding deforestation requires financial mechanisms that make retention of forests economically competitive with the currently often preferred option to seek profits from other land uses. According to the model calculations, even relatively low carbon incentives of around 6 $/tC/5 year, paid for forest carbon stock retention or carbon taxes of 12 $/tC would suffice to effectively cut emissions from deforestation by half. Taxes revenues would bring about annual income of US$6 bn in 2005 to US$0.7 bn in 2100. The financial means required for incentives are estimated to range from US$3 bn to US$ 200 bn per year, depending on the design of the avoided deforestation policy. Our scenario, where incentives are payed in regions where deforestation will appear and the payment has an effect, estimates the necessary funds to cut emissions from deforestation in half in the magnitude of some US$ 33 bn per year, without including costs for transaction, observation and illegal logging protection. Increasing the value of forest land and thereby make it less easily prone to deforestation would act as a strong incentive to increase productivity of agricultural and fuelwood production.

Methods

The model is based mainly on the global afforestation model of [4] and calculates the net present value of forestry with equation (1 – 16) and the net present value of agriculture with equation (17 – 20). Main drivers for the net present value of forestry are income from carbon sequestration, wood increment, rotation period length, discount rates, planting costs and wood prices. Main drivers for the net present value of agriculture on current forest land are population density, agricultural suitability and risk adjusted discount rates.

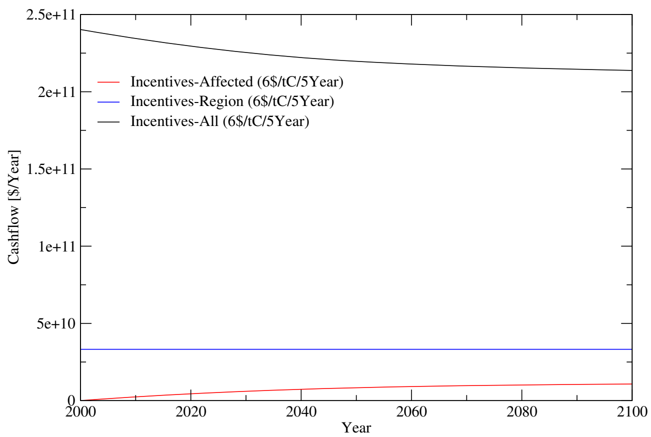

Figure 8
Expenditure until 2100 for different Incentive payment Strategies. *Incentives*... Periodic payments for standing biomass, *All*... Payments are done, without considering the effectiveness of the payment, in all regions, *Region*... Payments are done in regions where the payments protect forest against deforestation, *Affected*... Payments are done for forests where the payments protect them against deforestation.

These two values are compared against each other and deforestation is subsequently predicted to occur when the agricultural value exceeds the forest value by a certain margin. When the model comes to the result, that deforestation occurs, the speed of deforestation was constraint by estimates given by equation (24). The speed of deforestation is a function of sub-grid forest share, agricultural suitability, population density and economic wealth of the country.

All symbols in the following equations are explained in the section "Abbreviations".

Net present value of forestry

The net present value of forestry is determined by the planting costs, the harvestable wood volume, the wood-price and benefits from carbon sequestration.

For existing forests which are assumed to be under active managment the net present value of forestry given multiple rotations (F_i) over the simulation horizon is calculated from the net present value for one rotation (f_i) (equation 1). This is calculated by taking into account the planting costs (cp_i) at the begin of the rotation period and the income from selling the harvested wood ($pw_i \cdot V_i$) at the end of the rotation period. Also the benefits from carbon sequestration are included denoted as (B_i).

The planting costs (eq. 3) are calculated by multiplying the planting costs of the reference country (cp_{ref}) with a price index (px_i) and a factor which describes the share of natural regeneration (pr_i). The ratio of plantation to natural regeneration is assumed to increase with increasing yield for the respective forests (eq. 4). The price index (eq. 5) is calculated using the purchasing power parity of the respective countries. The stumpage wood price (eq. 6) is calculated from the harvest cost free income range of wood in the reference country. This price is at the lower bound when the population density is low and the forest share is high and at the higher bound when the population density is high and the forest share is low. The price is also multiplied with a price index converting the price range from the reference country to the examined country. The population-density and forest-share was standardized

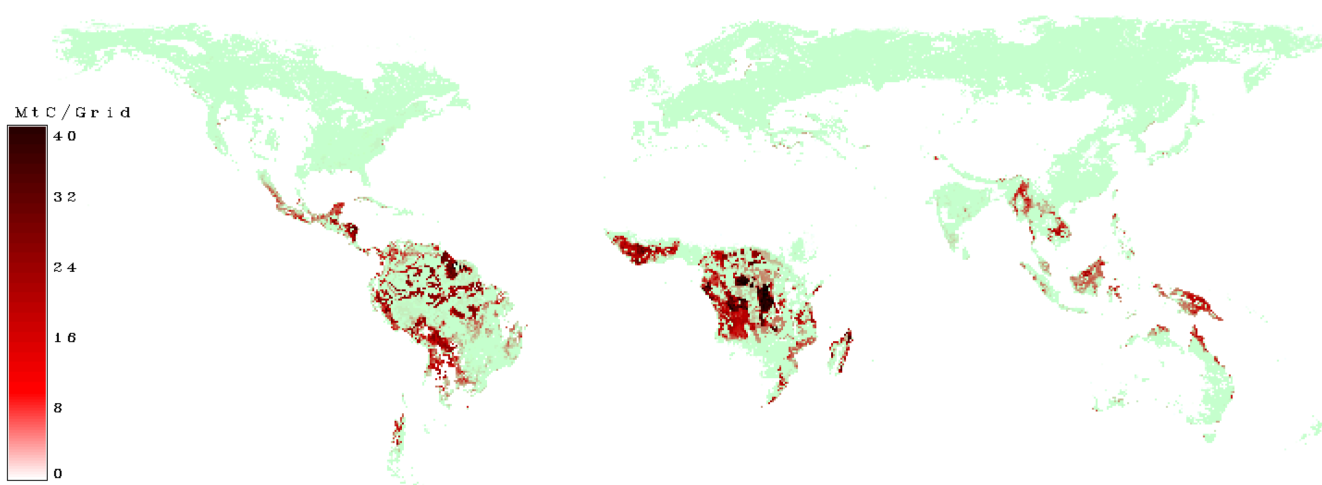

Figure 9
Removed Biomass without a carbon price. Green areas show grids where nowadays forests can be found. Red areas indicate grids where deforestation will occur in a scenario without carbon prices.

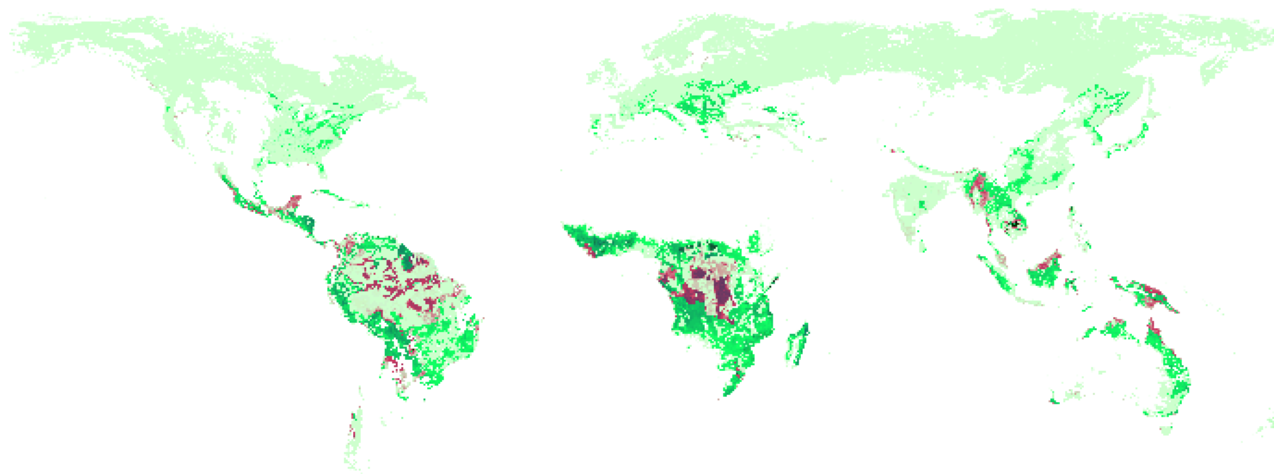

Figure 10
Saved Biomass by 12$/tC (Burn Sell). Light green show grids where nowadays forests can be found. Dark green areas indicate grids where forest biomass can be saved by introducing a carbon price of 12$/tC compared to the baseline scenario. Red ares indicate grids where there will still be deforestation.

between 1 and 10 by using equation (7) and equation (8) respectively.

The harvested volume (V_i) is calculated by multiplying the mean annual increment (MAI_i) with the rotation period length (R_i) accounting for harvesting losses (eq. 9).

The rotation period length (eq. 10) depends on the yield. Fast growing stands have a short and slow growing sites a long rotation length. In this study the rotation length is in the range between 5 and 140 years.

The mean annual increment (eq. 11) is calculated by multiplying the estimated carbon uptake (ω_i) and a transformation factor which brings the carbon weight to a wood volume ($C2W_i$). The carbon uptake (ω_i) is calculated by multiplying the net primary production (NPP_i) with a factor describing the share of carbon uptake from the net primary production (eq. 12).

The benefits of carbon sequestration (eq. 13) are calculated by discounting the annual income from additional carbon sequestration and subtracting the expenses incurred from harvesting operations and silvicultural production. At the end of a rotation period the harvested carbon is still stored in harvested wood products and will come back to atmosphere with a delay. This is considered in the factor (θ_i) which shares the harvested wood volume to short and long living products(eq. 14).

The effective carbon price represents the benefit which will directly go to the forest owner. In equation (16) a factor describing the percentage of the transaction cost free carbon price is used. A factor $leak_i$ is calculated as the average of the percentile rank from "political stability", "government effectiveness" and "control of corruption" [5].

$$F_i = f_i \cdot [1-(1+r)^{-R_i}]^{-1} \quad (1)$$

$$f_i = -cp_i + pw_i \cdot V_i + B_i \quad (2)$$

$$cp_i = cp_{ref} \cdot pr_i \cdot px_i \quad (3)$$

$$pr_i = \begin{cases} 0 & MAI_i < 3 \\ (MAI_i - 3)/6 & 3 \le MAI_i \le 9 \\ 1 & MAI_i > 9 \end{cases} \quad (4)$$

$$px_i = \frac{PPP_i}{PPP_{ref}} \quad (5)$$

$$pw_i = pw_{min} - \frac{pw_{max} - pw_{min}}{99} + \frac{pw_{max} - pw_{min}}{99} \cdot SPd \cdot SNFs \cdot px_i \quad (6)$$

$$SPd = \begin{cases} 1 + \dfrac{Pd \cdot 9}{100} & Pd \le 100 \\ 10 & Pd > 100 \end{cases} \quad (7)$$

$$SNFs = 1 + (1 - Fs) * 9 \quad (8)$$

$$V_i = MAI_i \cdot R_i \cdot (1 - HL_i) \quad (9)$$

$$R_i = \begin{cases} 5 & MAI_i > 180/10 \\ \dfrac{600-|MAI_i - 6| \cdot 50}{MAI_i} & \dfrac{10}{3} \le MAI_i \le \dfrac{180}{10} \\ 140 & MAI_i < 10/3 \end{cases} \qquad (10)$$

$$MAI_i = \omega_i \cdot C2W \qquad (11)$$

$$\omega_i = NPP_i \cdot CU \qquad (12)$$

$$B_i = epc_i \cdot \omega_i \cdot (1-b_i) \cdot \{r^{-1} \cdot [1-(1+r)^{-R_i}] - R_i \cdot (1-\theta_i) \cdot (1+r)^{-R_i}\} \qquad (13)$$

$$\theta_i = (1 - \frac{dec_{llp} \cdot frac_{llp}}{dec_{llp} + r} - \frac{dec_{slp} \cdot frac_{slp}}{dec_{slp} + r}) \cdot (1 - frac_{sb}) + (1 - frac_{sb}) * frac_{sb} \qquad (14)$$

$$frac_{slp} = 1 - frac_{llp} \qquad (15)$$

$$epc_i = pc_i \cdot leak_i \qquad (16)$$

Net present value of agriculture

The net present value of agriculture (A_i) is calculated with a two-factor Cobb-Douglas production function (equation 17). It depends on the agriculture suitability and the population density. A high agriculture suitability and a high population density causes high agricultural values. The value ranges between a given minimum and a maximum land price. The parameters a_i and γ_i determine the relative importance of the agriculture suitability and the population density and v_i determines the price level for land. The agriculture suitability and the population density are normalized between 1 and 10.

$$A_i = v_i \cdot SAgS_i^{\alpha_i} \cdot SPd_i^{\gamma_i} \qquad (17)$$

$$SAgS_i = \begin{cases} 10 & AgS_i \ge 0.5 \\ 1 + 9 \cdot AgS/0.5 & AgS_i < 0.5 \end{cases} \qquad (18)$$

$$\alpha_i = \frac{\ln(PL_{max}) - \ln(PL_{min})}{2 \cdot \ln(10)} \qquad (19)$$

$$\gamma_i = \alpha_i \qquad (20)$$

Decision of deforestation

The deforestation decision is expressed by equation (21). It compares the agricultural and forestry net present values corrected by values for deforestation and carbon sequestration. For the deforestation decision the amount of removed biomass from the forest is an important variable. The agricultural value needed for deforestation increases with the amount of timber sales and its concomitant flow to the HWP pool. On the other hand the agriculture value will be decreased by the amount of released carbon to the atmosphere. This mechanism is expressed by a deforestation value (DV_i, eq. 22). The model also allows for compensation of ancillary benefits from forests. This additional income is modeled either as a periodical income or a one time payment and will increase the forestry value by (IP_i). If it is a periodic payment it has to be discounted, which has been done in equation (23).

$$\text{Defor} = \begin{cases} \text{Yes} & A_i + DV_i > F_i \cdot H_i + IP_i \\ & \wedge \text{not Protected} \\ \text{No} & A_i + DV_i \le F_i \cdot H_i + IP_i \\ & \vee \text{Protected} \end{cases} \qquad (21)$$

$$DV_i = BM_i \cdot \left\{ pw_i \cdot C2W \cdot (1 - HL_i) - epc_i \cdot \left[(1+r) \cdot \left(\frac{frac_{llp} \cdot dec_{llp}}{dec_{llp} + r} + \frac{frac_{slp} \cdot dec_{slp}}{dec_{slp} + r} \right) \cdot (1 - frac_{sb}) + frac_{sb} \right] \right\} \qquad (22)$$

$$IP_i = (BM_i + BMP_i) \cdot pca_i \cdot \frac{(r+1)^{fr_i}}{(r+1)^{fr_i} - 1} \qquad (23)$$

There exist several ways of how financial transfers can be handled. Two mechanisms are realized in equation (21). One is to pay the forest owner to avert from the deforestation, the other is to introduce a carbon price that the forest owner gets money by storing carbon and paying for releasing it. The introduction of a carbon price focuses the money transfer to the regions where a change in biomass takes place. Payments to avoid emissions from deforestation can be transfered to cover all of the globe's forests, target to large "deforestation regions" or individual grids.

Deforestation rate

Once the principle deforestation decision has been made for a particular grid cell (i.e. the indicator variable $Defor_i$ = 1) the actual area to be deforested within the respective grid is to be determined. This is done by the auxiliary equation (24 – 25) computing the decrease in forest share. We model the deforestation rate within a particular grid as a function of its share of forest cover, agricultural suitability, population density and gross domestic product. The coefficients c_1 to c_6 were estimated with a generalized linear model of the quasibinomial family with a logit link. Values significant at a level of 5% were taken and are shown in table 1. The parameters of the regression model were estimated using R [6]. The value of c_0 was determined upon conjecture and directly influences the maximum possible deforestation rate. For our scenarios the maximum possible deforestation is set to 5% of the total land area per year. That means, a 0.5° × 0.5° grid covered totally with forests can not be deforested in a shorter time period than 20 years.

$$Fdec_i = \begin{cases} 0 & \text{Defor} = \text{No} \\ Fs_i & Ftdec_i > Fs_i \wedge \text{Defor} = \text{Yes} \\ Ftdec_i & Ftdec_i \le Fs_i \wedge \text{Defor} = \text{Yes} \end{cases} \qquad (24)$$

Table 1: Coefficients for equation (25) – Deforestation speed

Coef	Estimate	Std. Error	Pr(> |t|)	
c_0	0.05	-	-	
c_1	-1.799e+00	4.874e-01	0.000310	***
c_2	-2.200e-01	9.346e-02	0.019865	*
c_3	-1.663e-01	5.154e-02	0.001529	**
c_4	4.029e-02	1.712e-02	0.019852	*
c_5	-5.305e-04	1.669e-04	0.001789	**
c_6	-1.282e-04	3.372e-05	0.000206	***

$$Ftdec_i = \begin{cases} 0 & Fs_i = 0 \vee AgS_i = 0 \\ x_i & Fs_i > 0 \wedge AgS_i > 0 \end{cases} \quad (25)$$

$$x_i = \frac{c_0}{1 + e^{-(c_1 + \frac{c_2}{Fs_i} + \frac{c_3}{AgS_i} + c_4 \cdot Pd_i + c_5 \cdot Pd_i^2 + c_6 \cdot GDP_i)}} \quad (26)$$

The deforestation rates (Ft_{dec}) were taken from [2], where the forest area from 1990, 2000 and 2005 for each country was given. For the estimation of the model parameters the area difference between 1990 and 2005 was used to infer the deforestation rate. All values which showed an increase of the forest area have been set to 0, because the model should only predict the deforestation. Countries with an increasing forest area have a deforestation rate of 0. It should be mentioned that the change rate is based on the total land area in the grid i and not on the current forest area.

By using c_2/F_s the model can only be used on grid's where there is some share of forest. This makes sense, because on places where there is no forest, no deforestation can appear. The model will only be usable on grids where forests occur. Therefore, for parameterization, the average agricultural suitability and the population density of a country are also only taken from grids which indicate forest cover.

Development of forest share

After calculating the deforestation rate, the forest share has to be updated each year with equation (27) assuring that the forest share stays within the permissible range of 0–1.

$$Fs_{i,year} = \begin{cases} fsx_{i,year} & fsx_{i,year} \leq 1 - (Bul_i + Crl_i) \\ 1 - (Bul_i + Crl_i) & fsx_{i,year} > 1 - (Bul_i + Crl_i) \end{cases} \quad (27)$$

$$fsx_{i,\,year} = Fs_{i,\,year-1} - F_{i,\,dec} \quad (28)$$

Aboveground carbon in forest biomass

The model describes the area covered by forests on a certain grid. It can also describe the forest biomass if the average biomass on a grid is known and the assumption was made, that the biomass in forests on the grid is proportional to the forest area.

For this reason a global carbon map of aboveground carbon in forest biomass, was created, based on country values from [2]. By dividing the given total carbon, for each country, with the forest area of the country, the average biomass per hectare can be calculated. Now the assumption was made, that the stocking biomass per hectare on sites with a higher productivity is higher than on sites with a low productivity. Not for every country with forests [2] gives values of the stocking biomass. So a regression, describing the relation between tC/ha and NPP, was calculated and the biomass of grids of missing countries have been estimated to obtain a complete global forest biomass map.

Simulations

In the simulations the effect of different carbon-prices and/or incentives, for keeping forest, have been tested. The simulation period started in the year 2000 and ends in 2100. The decision, whether deforestation takes place or not and how fast it goes on, was done in one year time steps. Scenario drivers, available on coarser time resolution (e.g. population density), have been interpolated linearly between the given years.

Outputs of the simulations are trajectoria of forest cover, changes in carbon stocks of forests, and financial resources required to cut emissions from deforestation under varying scenario assumptions.

Data

The model uses several sources of input data some available for each grid, some by country aggregates and others are global. The data supporting the values in table 2 are known for each grid. Some of the values are also available for time series.

Beside the datasets, available at grid level, the purchasing power parity PPP [7] from 1975–2003, the discount rates [8] for 2004, the corruption in 2005 [5] and the fraction

Table 2: Spatial dataset available on a 0.5° × 0.5° grid

Value	Year	Source
Land area	2000	[11]
Country	2000	[12]
NPP	-	[10]
Population density	1990 – 2015	[13]
Population density	1990 – 2100	[14]
GDP	1990 – 2100	[14]
Buildup	2010 – 2080	[15]
Crop	2010 – 2080	[15]
Protected	2004	[16]
Agriculture suitability	2002	[17]
Biomass	2005	Self
Forest area	2000	[11]

of long living products for the time span 2000–2005 [2] are available for each country (table 3).

The values of table 4 are used globally. Monetary values are transformed for each country with their price index. Brazil was taken as the price-reference country as described in [8] and [9].

In figure 11 the net primary productivity taken from [10] is shown. The values range up to 0.75 gC/m^2/year. The highest productivity is near the equator.

In figure 12 the population density in 2000 and in figure 13 in the year 2100 is shown. It can be seen, that the highest population densities are reached in India and in south-east Asia. The densities are also quite high in Europe and Little Asia, Central Africa and the coasts of America. The map of 2100 shows an increase in India and in south-east Asia.

Figure 14 shows a map of the current forest, crop and buildup land cover. Large regions are covered by forests. Adjacent to the forests, large areas, used for crop production, can be seen.

In figure 15 the suitability for agriculture is shown. Most of the high suitable land is used today for crop production (see figure 14).

Figure 16 shows the carbon in forests. It can be seen, that the highest densities are located near the tropical belt. One reason for this is, that the biomass in tropical forests is high. Note that this picture shows the tons of carbon per grid and the grid size is 0.5° × 0.5° so the grid has it's largest size near the equator.

Figure 17 shows the purchasing power parity which was used to calculate a price-index. It can be seen that the poorest countries are in Africa and the richest in North America, Europe, Australia and Japan.

Figure 18 shows the discount-rates given in [8]. Here also the richest countries have the lowest discount rates.

Figure 19 shows the effectiveness of the carbon incentives. In low risk countries nearly all of the spent money will be used for maintaining forest sinks in risky countries not all of the money will come to the desired sink.

Figure 20 shows the proportion of harvested wood entering the long living products pool [2].

Abbreviations

α_i: Importance of agriculture

γ_i: Importance of population

ν_i: Land price level = minimum land price of reference country × price index (px_i) [$/ha]

Table 3: Country level values

	Source
Discount rate	[8]
Fraction of long living products	[2]
Corruption	[5]
PPP	[7]

Table 4: Global values

Baseline	0.1
Decay rate long	ln(2)/20
Decay rate short	0.5
Factor carbon uptake	0.5
Frequency of incentives payment	5 years
tC to m^3	4
Harvest losses	0.3
Hurdle	1.5
Maximum rotation interval	140 years
Minimum rotation interval	5 years
Planting costs	800 $/ha
Carbon price	0–50 $/tC
Carbon price incentives	0–50 $/tC
Minimum Land price	200 $/ha
Maximum Land price	900 $/ha
Minimum wood price	5$/ha
Maximum wood price	35$/ha

ω_i Carbon uptake per year [tC/year/ha]

θ_i : Fraction of carbon benefits in products [1]

A_i: Net present value of agriculture [$/ha]

AgS_i: Agricultural suitability [0–1]

b_i: Baseline, how much carbon uptake will be if there is no forest, e.g. 0.1 [1]

BMP_i: Biomass in Products [tC/ha]

BM_i: Aboveground living wood biomass [tC/ha]

B_i: Present value of carbon benefits [$/ha]

Bul: Share of buildup land [1]

$C2W$: Conversion factor form 1t Carbon to $1m^3$ wood [m^3/tC]

cp_i: Planting costs [$/ha]

cp_{ref}: Planting costs reference country [$/ha]

CU: Carbon uptake, share of NPP stored in wood [1]

Crl: Share of crop land [1]

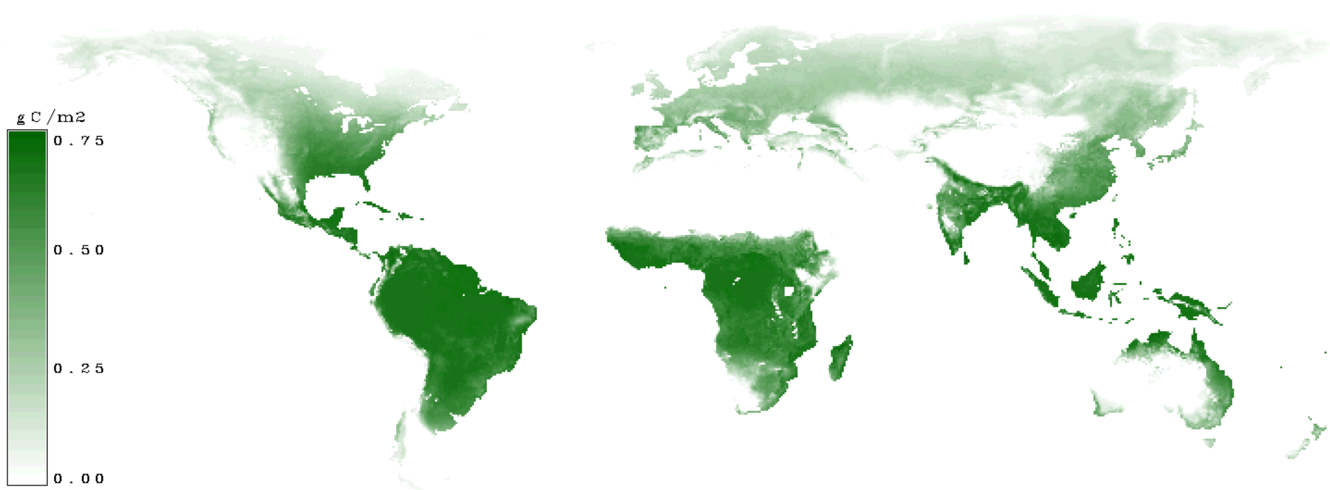

Figure 11
Net Primary Production (NPP). Areas with a high increment have a high net primary productivity and are indicated by dark green. Sites with low productivity are indicated by light green.

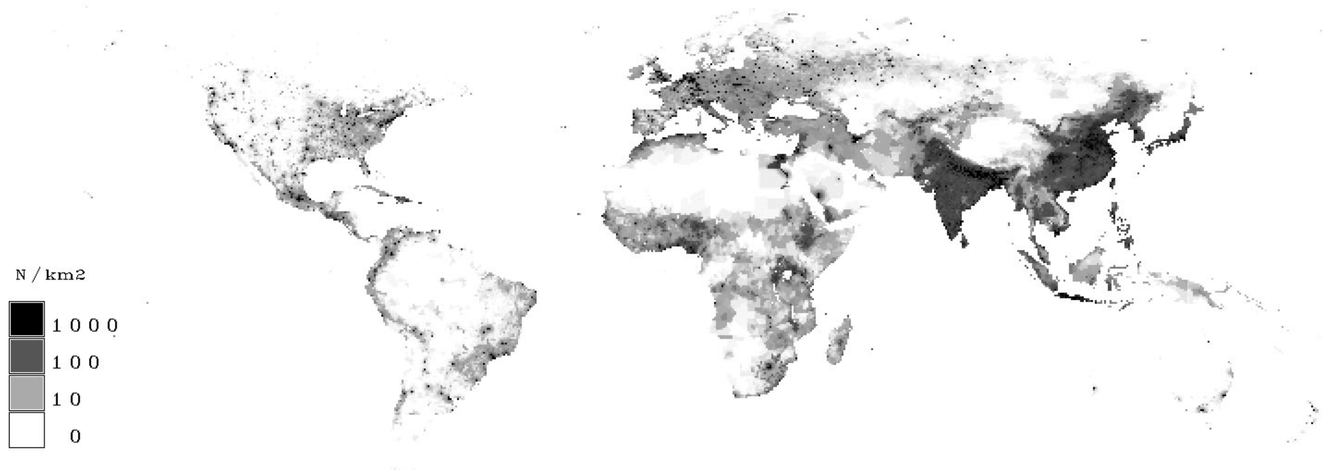

Figure 12
Population density in Year 2000. Grids with few people are given in white. A rising population density is marked by grey up to high population densities (≥1000 people/km²) which are indicated by black.

dec_{llp}: Decay rate of long living products e.g. 0.03 [1]

dec_{slp}: Decay rate of short living products e.g. 0.5 [1]

DV_i: Deforestation Value [\$/ha]

epc_i: Effectiv carbon price [\$/tC]

f_i: Net present value of forestry for one rotation period [\$/ha]

F_i: Net present value of forestry [\$/ha]

F_s: Actual share of forest [0–1]

F_{dec}: Decrease of the forest share

fr_i: Frequency of incentives money payment [Years]

$frac_{llp}$: Fraction of long living products e.g. 0.5 [0–1]

Figure 13
Population density in Year 2100. Grids with few people are given in white. A rising population density is marked by grey up to high population densities (≥1000 people/km²) which are indicated by black.

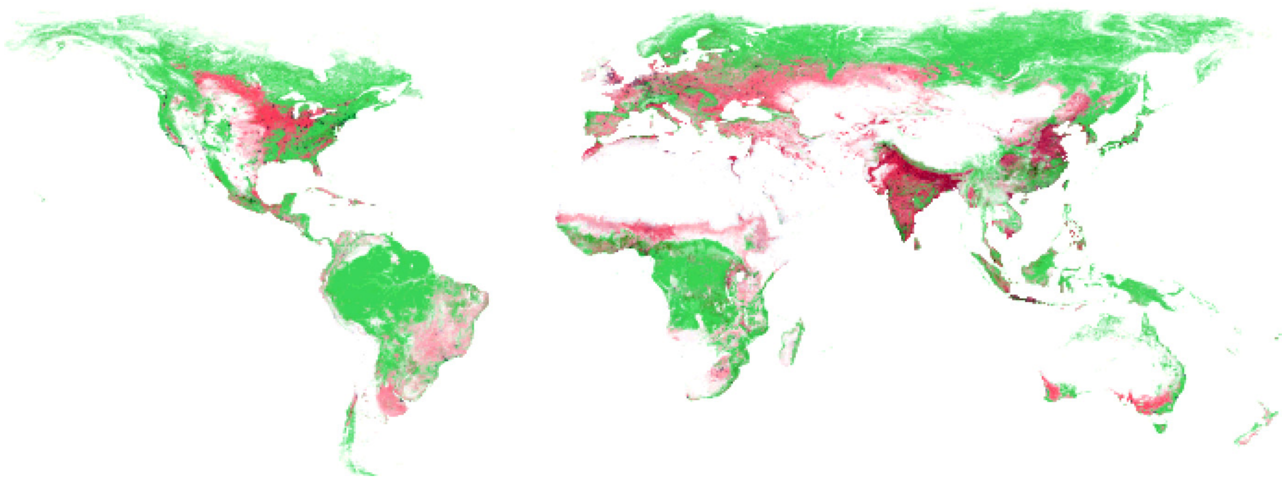

Figure 14
Forest, Crop and Buildup Land cover. Forests are shown in green, crop in red and buildup land in grey.

$frac_{sb}$: Fraction of slash burned area e.g. 0.9 [0–1]

$frac_{slp}$: Fraction of short living products e.g. 0.5 [0–1]

Fs: Forest area share [0–1]

Fs_{year}: Forest share of a certain year [1]

fsx_{year}: Theoretical forest share of a certain year [1]

Ft_{dec} : Theoretical decrease of the forest share

GDP: Gross domestic product [$\$_{1995}$/Person]

H_i: Hurdle e.g. 1.5 [1]

HL_i: Harvesting losses e.g. 0.2 [1]

i: Grid number

$leak_i$: Factor of money which will in real reach the forest [1]

IP_i: Incentive payment [\$/ha]

MAI_i: Mean annual wood volume increment [m³/ha]

NPP_i: Net primary production [tC/ha/year]

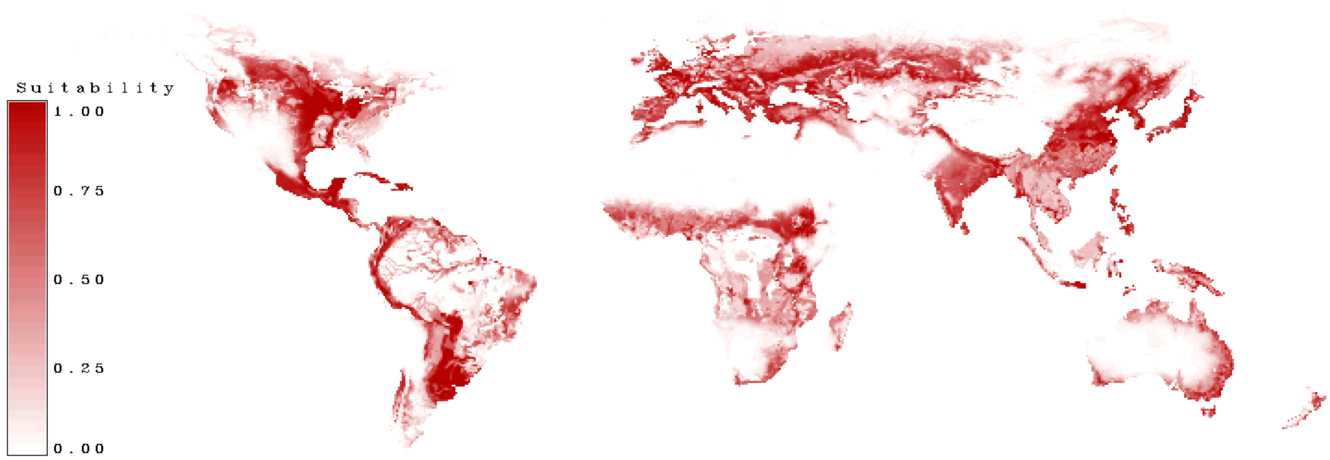

Figure 15
Agriculture suitability. High suitability for agriculture is marked in dark red. White areas are not suitable for agriculture.

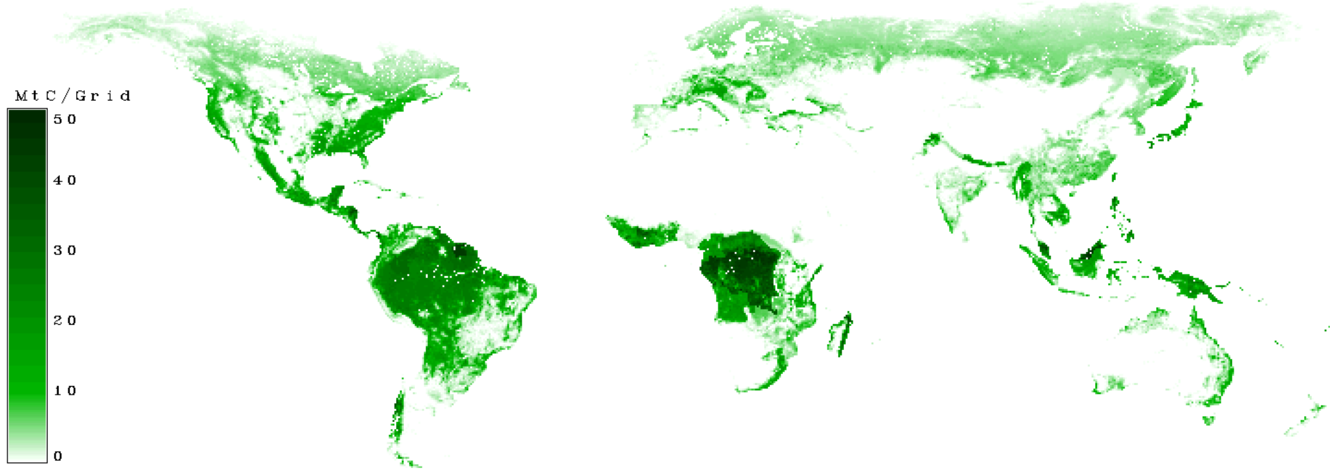

Figure 16
Carbon in Forest biomass. Regions with no carbon in forests are white. Regions with high values of carbon in forests are dark green.

pc_i: Carbon price [$/tC]

pca_i: Incentives carbon price [$/tC/$fr_i$]

Pd_i: Population density [People/km^2]

PL_{max}: Maximal land price of reference country × price index (px_i) [$/ha]

PL_{min}: Minimal land price of reference country × price index (px_i) [$/ha]

PPP_i: Purchasing power parity [$]

PPP_{ref}: Purchasing power parity of reference country [$]

pr_i: Ratio of area planted [0–1]

pw_i: Stumpage wood price [$/m^3]

pw_{max}: Maximum revenue of wood, e.g. 35$/fm [$/fm]

Pw_{min}: Minimum revenue of wood, e.g. 5$/fm [$/fm]

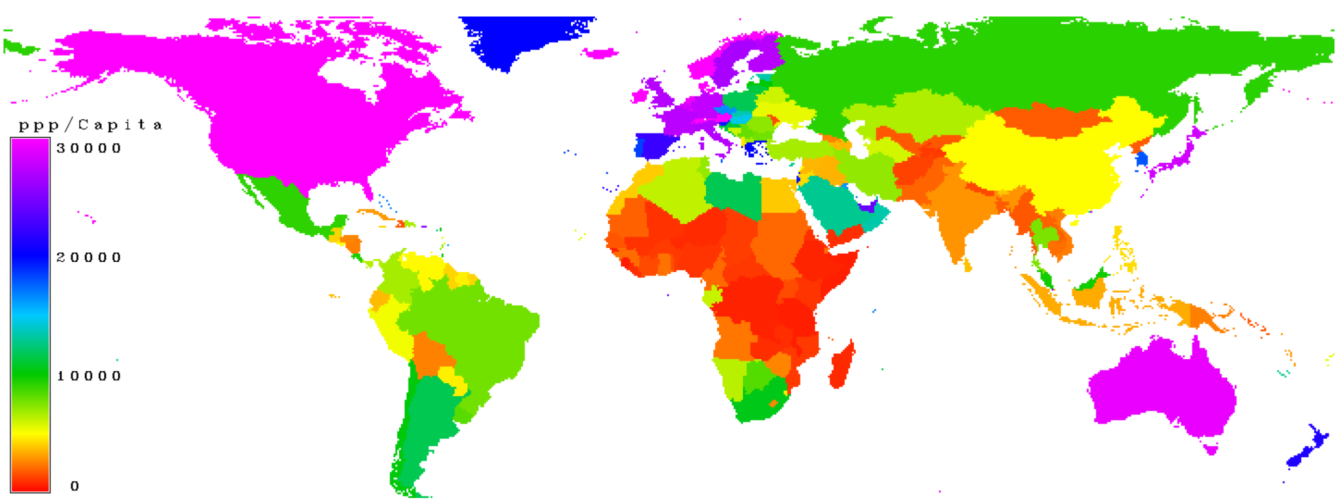

Figure 17
Purchasing Power Parity (PPP). Countries with a low purchasing power parity are marked in red, moderate is in green, high values in blue and very high in magenta.

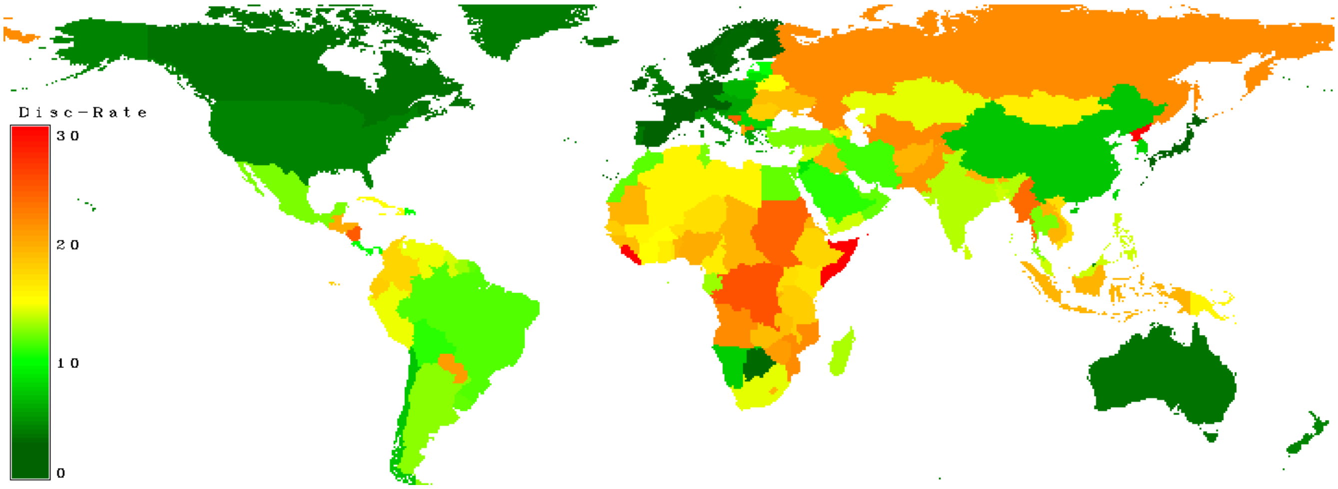

Figure 18
Discount Rate. Countries with a low discount rate are marked in dark green, moderate countries in yellow and countries with a high rate in red.

px_i: Price index [1]

r: Discount rate [e.g. 0.05]

R_i: Rotation interval length [years]

$SAgS_i$: Standardized agricultural suitability [1-10]

SFs: Standardized not forest area share [1-10]

SPd: Standardized population density [1-10]

V_i: Harvest wood volume [m³]

x_i: Theoretical decrease of the forest share if $Fs_i > 0 \wedge AgS_i > 0$

Competing interests
The author(s) declare that they have no competing interests.

Authors' contributions
Georg Kindermann has developed the deforestation rate model, implemented the whole model, collected some data sources and organized them to be used for the imple-

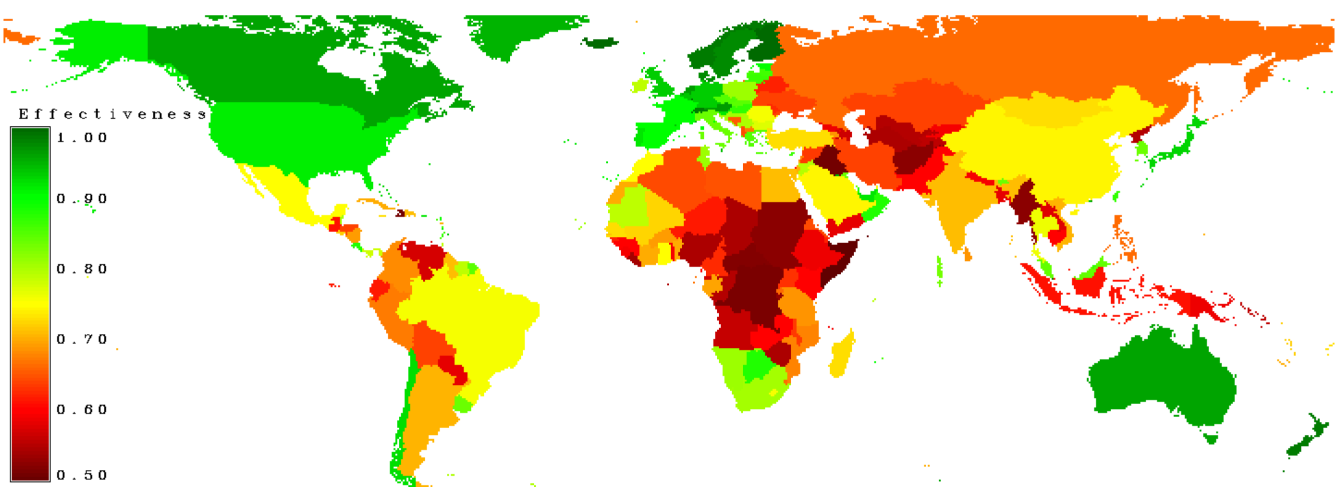

Figure 19
Effectiveness (Corruption). Countries with high values of corruption are marked in red, moderate countries in yellow and low values in green.

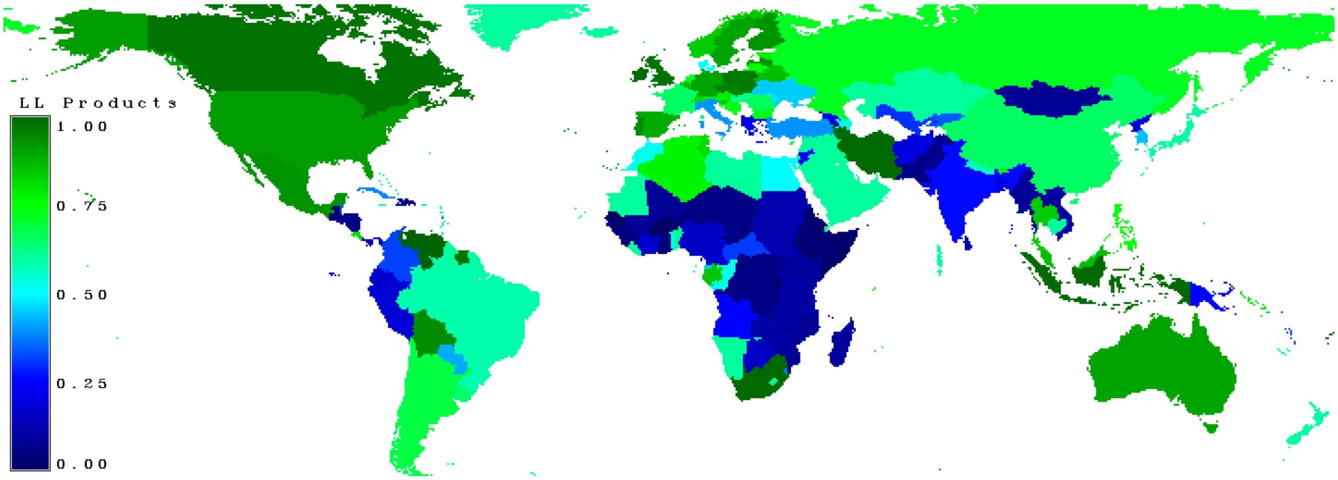

Figure 20
Share of long living products. Countries which use their wood mainly for fuel-wood are marked in blue, those who use it for sawn-wood are in green.

mentation, runs the simulations, created figures and tables and wrote a first draft of the paper.

Michael Obersteiner developed the core model describing the forest value, agricultural value and decision of deforestation, worked on the paper, introduced the maximum tax income and contributed to the payment possibilities.

Ewald Rametsteiner contributed to the carbon price and incentives model and their practical implementation, worked on the paper and brought in many background informations.

Ian McCallum collected and organized the data source and produced some figures of the paper.

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References

1. IPCC International Panel on Climate Change, ed Robert T Watson and Core Writing Team: *Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Integovernmental Panel on Climate Change* 2001 [http://www.ipcc.ch/pub/syreng.htm]. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA
2. FAO: *Global Forest Resources Assessment 2005, Progress towards sustainable forest management Volume 147*. FAO Forestry Paper. Rome: ood and Agriculture Organization of the United Nations; 2005.
3. Marland G, Boden T, Andres R: **Global, Regional, and National CO2 Emissions.** In *Trends: A Compendium of Data on Global Change* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.; 2006.
4. Benítez PC, Obersteiner M: **Site identification for carbon sequestration in Latin America: A grid–based economic approach.** *Forest Policy and Economics* 2006, **8:**636-651.
5. Kaufmann D, Kraay A, Mastruzzi M: *Governance Matters IV: Governance Indicators for 1996–2004, World Bank Policy Research Working Paper Series No. 3630. World Bank* 2005 [http://ssrn.com/abstract=718081].
6. R Development Core Team: *R: A language and environment for statistical computing* 2005 [http://www.R-project.org]. R Foundation for Statistical Computing, Vienna, Austria [ISBN 3-900051-07-0].
7. World Bank: *World Development Indicators. World Bank* 2005.
8. Benítez P, McCallum I, Obersteiner M, Yamagata Y: **Global Supply for Carbon Sequestration: Identifying Least-Cost Afforestation Sites Under Country Risk Consideration.** Tech. rep., International Institute for Applied System Analysis; 2004.
9. Obersteiner M, Alexandrov G, Benítez PC, McCallum I, Kraxner F, Riahi K, Rokityanskiy D, Yamagata Y: **Global Supply of Biomass for Energy and Carbon Sequestration from Afforestation/Reforestation Activities.** *Mitigation and Adaptation Strategies for Global Change* 2006:1381-2386.
10. Alexandrov GA, Yamagata Y, Oikawa T: **Towards a Model for Projecting Net Ecosystem Production of the World Forests.** *Ecological Modelling* 1999, **123:**183-191.
11. JRC: *The Global Land Cover Map for the Year 2000. GLC2000 database* 2003 [http://www-gvm.jrc.it/glc2000]. European Commision Joint Research Centre
12. CIESIN: **Center for International Earth Science Information Network (CIESIN), Columbia University; and Centro Internacional de Agricultura Tropical (CIAT). Gridded Population of the World Version 3 (GPWv3): National Boundaries. Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University.** 2005 [http://sedac.ciesin.columbia.edu/gpw].

13. CIESIN: **Center for International Earth Science Information Network, Columbia University; and Centro Internacional de Agricultura Tropical (CIAT). Gridded Population of the World Version 3 (GPWv3): Population Density Grids. Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University.** 2005 [http://sedac.ciesin.columbia.edu/gpw].
14. Grubler A, Nakicenovic N, Riahi K, Wagner F, Fischer G, Keppo I, Obersteiner M, O'Neill B, Rao S, Tubiello F: **Integrated assessment of uncertainties in greenhouse gas emissions and their mitigation: Introduction and overview.** *Technological Forecasting and Social Change* in press.
15. Tubiello FN, Fischer G: **Reducing climate change impacts on agriculture: Global and regional effects of mitigation, 2000–2080.** *Technological Forecasting and Social Change* in press.
16. WDPA Consortium: **World Database on Protected Areas. Copyright World Conservation Union (IUCN) and UNEP-World Conservation Monitoring Centre (UNEP-WCMC).** 2004.
17. Ramankutty N, Foley JA, Norman J, McSweeney K: **The global distribution of cultivable lands: current patterns and sensitivity to possible climate change.** *Global Ecology & Biogeography* 2002, **11(5):**377-392.

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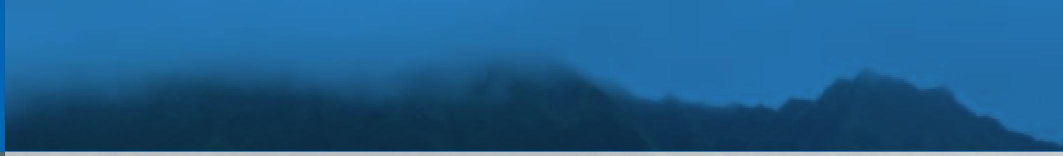

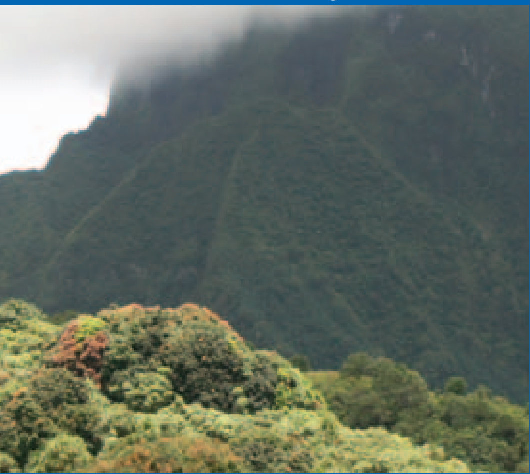

Reducing Emissions from Deforestation and Forest Degradation: A Systematic Approach

#08 ▪ December 2009

As up to 20 percent of global anthropogenic greenhouse gas emissions result from deforestation activities, the reduction of emissions from deforestation and degradation of forests (REDD) is a major theme of the ongoing negotiations under the United Nations Framework Convention on Climate Change (UNFCCC). This briefing looks at the fundamental issues underlying REDD, as well as the challenges involved in current proposals to implement a trading scheme for REDD credits.

Summary

■ Trees continuously capture and store carbon. However, when destroyed (e.g., by fire), they release carbon dioxide (CO_2) into the atmosphere. With the living carbon storage capacity of much of the world's tropical forests diminishing at a rapid rate through deforestation and forest degradation, many believe that the reduction of emissions from deforestation and degradation of forests (REDD) must be a fundamental part of overall approaches to climate change mitigation. Avoiding deforestation, however, requires the introduction of financial mechanisms that make the retention of forests economically competitive.

■ Efforts are currently under way to elaborate a scheme whereby credits could be issued for REDD and traded in the same way as carbon credits are traded under the clean development mechanism of the Kyoto Protocol. Any REDD credit–generating system is likely to operate under the principles of the ministerial statement issued at COP14 in Poznan in December 2008. This incorporates: (1) development of transparent, collaborative, balanced, and inclusive international arrangements to support national REDD efforts; and (2) elaboration of a reliable framework to measure, report, and verify (MRV) emission reductions.

■ The main challenges to the implementation of a viable REDD scheme are: (1) how to generate globally consistent emission reference scenarios at the country level from which to derive fully MRV'd REDD credits; and (2) elaboration of a "water-tight" financial mechanism whereby REDD credits, in the same way as carbon credits, could be issued and traded for avoided deforestation.

■ While any REDD actions at national, regional, or project level would be tailored to maximize emission reductions, they should recognize the different ecological and social co-benefits of forests, namely: (1) the conservation of terrestrial biodiversity; (2) their important cultural, spiritual, and recreational roles in many societies; and (3) their contribution to the economic life of hundreds of millions of people.

■ The establishment of an "International Emission Reference Scenario Coordination Center" (IERSCC) as a basis for deriving fully MRV'd REDD credits and an "International Emission Investment Reserve" (IEIR) to finance REDD activities are discussed here, along with the safeguarding of forest co-benefits under a REDD scheme.

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GEOBENE

SIXTH FRAMEWORK PROGRAMME

COOPERATION

"To guarantee a streamlined application of REDD methodologies and data, the establishment of an International Emission Reference Scenario Coordination Center is proposed."

Implementing a workable REDD scheme

REDD can be successful only if the reduction of emissions from forests can be made measurable, reportable, and verifiable, and if sufficient financial incentives are provided in a timely manner. Two international institutions for monitoring and financing as part of an overall fair, effective, and efficient overall framework for REDD are proposed here (see chart, p.3). They are intended to catalyze the current policy process by providing pragmatic and flexible solutions for the design and implementation of a REDD scheme.

Establishment of an "International Emission Reference Scenario Coordination Center" to set reference levels and verify emission reductions for REDD

As avoided deforestation and degradation in developing countries would be matched by financial compensation from Annex I countries, the first key requirement of any potential REDD mechanism, acceptable to both developing and developed countries under a market or fund mechanism, would be for REDD actions/credits to be based on measurable, reportable, and verifiable (MRV) data. This would include setting MRV'd reference levels (RL) to prevent parties (projects and/or countries) setting inflated baselines in order to generate more carbon credits for future emission reductions:

- The first step would be to establish national REDD reference levels in a fair, transparent, and efficient way as a basis for assessing future emission reductions. RL would be based on measurable indicators of country-specific drivers of deforestation, national circumstances, and historic deforestation rates—a multitude of methodologies for the collection and interpretation of forest area change, emission data, and deforestation drivers already exist. However, many developing countries still lack the necessary capacity to fulfill these requirements.

- To guarantee a streamlined application of REDD methodologies and data, the establishment of an International Emission Reference Scenario Coordination Center (IERSCC) is proposed. This would act as an independent global clearinghouse for harmonized data to be used in implementing reference level methodologies and in future REDD monitoring. The IERSCC would be tasked with collecting, reporting, and subsequent processing of Earth observation, deforestation- and degradation-driver information in a globally consistent manner. It would also assist, coordinate, and supervise the computation of national reference scenarios according to rules negotiated under the UNFCCC. National governments could request support, when needed, from the IERSCC in calculating their national RL and subsequent emission reductions.

- The IERSCC could serve as a central coordinating REDD capacity-building institution for monitoring and RL development in conjunction with other capacity building efforts such as the UN-REDD Programme. If possible, the IERSCC should be integrated into existing institutions like the Intergovernmental Panel on Climate Change (IPCC) or the UNFCCC secretariat to limit its administrative burdens.

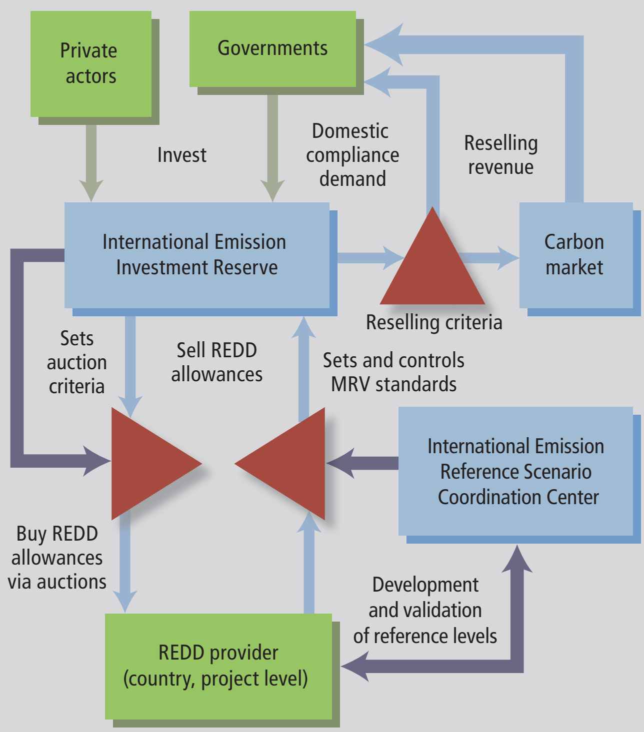
Establishment of an "International Emission Investment Reserve" to finance REDD

According to the *Eliasch Review*, the cost of halving net global CO_2 emissions from forests by 2030 is estimated at US$17–33 billion annually, but only if REDD is included in global emissions trading. However, simply adding avoided deforestation carbon credits to the existing carbon trading mechanisms threatens a flood of cheaper credits into global and linked domestic carbon markets due to the potentially high quantity and relatively low prices of REDD credits.

REDD carbon credits are estimated to emerge in the range of US$4–10 per tonne of carbon avoided. A 2007 study from the Woods Hole Research Center concluded that 94 percent of Amazon deforestation could be avoided at a cost of less than US$5 per tonne of carbon. These levels compare to the US$25 to US$35 per tonne current trading range of existing offset carbon credits. Thus if REDD credits were introduced to the global carbon market, industrialized countries could find it easy to fulfill most of their targets with cheap REDD. Moreover, both the potentially high quantity and low quality of REDD credits in the carbon markets could threaten the climate integrity of REDD and counter other climate protection targets:

- The establishment of an International Emission Investment Reserve (IEIR) is proposed to serve as a special form of investment fund for REDD. The IEIR would be a public investment scheme managed and administrated by a board of trustees consisting of investors and other relevant stakeholders. Its integration into existing international institutions such as the UNFCCC would be helpful in achieving legitimacy and avoiding administrative overburdening. The majority of capital for the IEIR would be provided by Annex I governments based on politically negotiated mandatory investment pledges to increase the trust in the scheme. Other investment sources would be flexible and could include private investments.

- The functioning of the IEIR can be described as follows:
  - REDD providers (developing country governments and/or private carbon projects) auction their yet-to-be-created REDD units to the IEIR. The unit price would be below the carbon-market-credit value and possibly discounted because of implementation risk and measurement uncertainties. The price would also be influenced by the amount of co-benefits secured by the emission reduction units claimed.
  - The auction mechanism in question is the second-price sealed-bid auction. Under this procedure, sellers of verified REDD credits would submit to the IEIR sealed bids proposing a minimum selling price per fixed unit or a maximum selling quantity per fixed price (the seller's "best price"). The highest REDD bidder is able to buy the credits at the second-best selling price per fixed unit or the second-maximum selling quantity per fixed price (the "second-best offer"). This continues until the finance is exhausted or the targeted emission reduction quantity of the IEIR is reached. This auctioning approach can ensure that a fixed quantitative REDD supply cap is achieved in a competitive setting.
  - The units are verified and then banked until market conditions are favorable for reselling them as fully fungible (interchangeable) MRV-based REDD credits to the carbon market. With many models projecting rising carbon credit prices, this will allow considerable reselling profits. To avoid market flooding the reselling can be conditional in terms of maximum number released per year, sufficient market demand, etc. The IEIR members would have an interest in reselling at higher market prices to increase revenue. Depending on its governing rules, the IEIR could act as a "central bank" to the carbon market controlling carbon price volatility.



REDD financing mechanism

Tropical rainforest on the island of Fatu Hiva, Marquesas Islands, French Polynesia © User:Sémhur / Wikimedia Commons / CC-BY-SA-3.0

Protecting co-benefits

As aggressive use of REDD policies could run into conflict with basic food-security issues and ultimately harm the very environments that REDD is seeking to safeguard, the protection of forest co-benefits under a REDD scheme is paramount.

To make provision of the essential co-benefits of REDD attractive and cost-efficient, it is proposed that the provision of co-benefits could be used either as a qualifier criterion or as a pricing criterion for the auction:

- If the REDD units, although MRV'd, fail to meet sustainability requirements, they are excluded from the auction. The sustainability requirements would be based on quantified and certified amount of ecosystem value points—ideally negotiated under the umbrella of the relevant UN conventions and charters.

- Alternatively, a co-benefit factor scale from 0.5 to 1.5 could be established, under which the price of REDD units offered by the winning bidder would be increased by a factor of 1.5 for maximum co-benefits or reduced by a factor of 0.5 for lowest possible co-benefit protection.

Conclusions

The new institutional arrangements outlined above could help overcome some of the deficiencies inherent in monitoring and financing schemes that currently hamper the effective inclusion of the forest sector as a critical component of carbon emissions mitigation strategies. However, the following factors must be taken into account:

- The methodology for setting RL and for assessing emission reductions must be carefully designed to prevent non-additional emission reductions (i.e., emissions that would have been reduced anyway) and an inflated supply of REDD credits—hence, the proposal for the International Emission Reference Scenario Coordination Center (IERSCC).

- The financing of REDD under an International Emission Investment Reserve would allow timely provision of large sums for REDD, enabling up-front financing for tackling deforestation in meaningful quantities. A powerful financing mechanism of this kind is needed for REDD to provide international resources without risking carbon market flooding.

- The use of the second-price sealed-bid auction, with an in-built system of co-benefit safeguards, would seem to offer the fairest method of assessing the price of units sold by REDD producers. It is hoped thereby to incentivize providers to provide a low unit price and high co-benefit performance.

- To reach these robust MRV standards, REDD readiness funding will be crucial in the coming years. The flexible structure of the IEIR will allow early and fluent phasing for this vital resource.

Further information

This Policy Brief is based on work from the following two research projects funded by the European Commission under its sixth and seventh framework programs, and coordinated by IIASA:

- The GEOBENE (Global Earth Observation – Benefit Estimation: Now, Next and Emerging) project aims to develop methodologies and analytical tools to assess societal benefits of global earth observation in the domains of disasters, health, energy, climate, water, weather, ecosystems, agriculture, and biodiversity. More at: www.geo-bene.eu

- The CC-TAME (Climate Change: Terrestrial Adaptation & Mitigation in Europe) project concentrates on assessing the impacts of agricultural, climate, energy, forestry and other associated land-use policies considering the resulting feed-backs on the climate system in the European Union. More at: www.cctame.eu

For in-depth information on the research summarized in this brief, see:

- Obersteiner M, Huettner M, Kraxner F, McCallum I, Aoki K, Boettcher H, Fritz S, Gusti M, Havlik P, Kindermann G, Rametsteiner E, Reyers B (2009). On fair, effective, and efficient REDD mechanism design. *Carbon Balance and Management*, 4:11 [doi:10.1186/1750-0680-4-11].

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Benefits of increased data resolution for European conservation planning

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Preface

This study contributes to the EU project "Global Earth Observation – Benefit Estimation: Now, Next and Emerging" (GEOBENE). Its objective is to develop methodologies and analytical tools to assess societal benefits of global earth observation. The project encompasses the domains of disasters, health, energy, climate, water, weather, ecosystems, agriculture, and biodiversity.

The Group on Earth Observation assumes that global earth observations are instrumental to achieve sustainable development. However, there have been no integrated assessments of their economic, social and environmental benefits to date.

The vision is to develop a high quality, timely, and comprehensive Global Earth Observation System of Systems (GEOSS). This includes a global biodiversity observation system that fulfills the data needs of the multilateral environmental agreements, governments, natural resource planners, scientific researchers and civil society, and integrates with ecological, agriculture, health, disaster, and climate monitoring policy.
A GEOSS biodiversity observation system would create a mechanism to integrate biodiversity data with other observations more effectively, leverage investments in local and national research and observation projects and networks for global analysis and modelling. It will build on existing efforts in order to collectively provide essential data and models for monitoring and reporting in the framework of the biodiversity-related conventions, and provide new information and tools for biodiversity research (Group on Earth Observations 2005).

This study contributes to the societal benefit area biodiversity and consists of two sub-studies. Part A deals with the modelling of explicit wetland habitat area for the European Union 25 countries. Part B shows how the implementation of these habitat area data influences the results of a habitat allocation model.

A Estimation of spatially explicit wetland distribution

Introduction

In Europe, the spatial distribution of wetlands is not well known except for large wetland areas or for wetlands of special ecological interest. Even those wetland areas, which have been identified on the behalf of European Environment Agency (EEA), correspond to wetland areas of ecological interest and represent only a rather small part of all wetland areas. This study deals with the development of the GIS-based wetland distribution model “Swedi”. By considering the matrix characteristics the model evaluates the spatially explicit distribution of existing wetland habitats and potential restoration sites. It simultaneously distinguishes different wetland types. The aim of this study is to compile spatially consistent information on wetlands differentiated by wetland types and characteristics, but initially regardless of their conservation status or restoration costs.

Definition of wetlands

Often wetland terms and definitions are not standardized. The RAMSAR Convention (Article 1.1) defines wetlands as "areas of marsh, fen, peat land or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters". In addition, the Convention (Article 2.1) determines that wetlands "may incorporate riparian and coastal zones adjacent to the wetlands". In wetlands water is present at or near the surface of the land also if only for varying periods of the year. Wetlands vary widely in soil, topography, climate, hydrology, water chemistry, vegetation, and other factors, also because of human disturbance. In our study we concentrate on the natural freshwater or inland wetlands as defined in table 1.

The definition of inland wetlands also includes marshes and wet meadows dominated by herbaceous plants that are most often human made as well as shrub- or tree-dominated swamps. In Europe, inland wetlands are most common on floodplains along rivers and streams, along the margins of lakes and ponds, and in other low-lying areas where the groundwater intercepts the soil surface or where precipitation sufficiently saturates the soil (vernal pools and bogs). Many of these wetlands are seasonal and may be wet only periodically.

Table 1. Wetland terms and their definitions

Common Wetland Names	Definition
Peatland	generic term of any wetland that accumulates partially decayed plant matter.
Bog	peat-accumulating wetland that has no significant inflows or outflows. Water and nutrient input entirely through precipitation; characterized by acid water, low alkalinity, and low nutrients. Peat accumulation usually dominated by acidophilic mosses, particularly sphagnum.
Fen	peat-accumulating wetland that receives some drainage from surrounding mineral soil. Usually dominated by sedge, reed (→reedswamp), shrub or forest (→swampforest). Surface runoff and/or ground water have neutral pH and moderate to high nutrients.
Marsh/ natural wet grasslands	permanently or periodically inundated site characterized by nutrient-rich water and emergent herbaceous vegetation (grasses, sedges, reed) adapted to saturated soil conditions. In European terminology a marsh has a mineral soil substrate and does not accumulate peat.
Reedswamp	marsh or fen dominated by Phragmites (common reed);
Swampforest	wetland dominated by trees, most often forested fen. Depends on nutrient-rich ground water derived from mineral soils.
Alluvial forest	Periodically inundated forest areas next to river courses.

Methods

GIS and spatial modelling are assumed to provide an appropriate tool to locate potential existing wetland areas as well as to illustrate the most suitable areas for wetland regeneration measures. This GIS model aims to depict the distribution of wetland areas at regional level and at coarse geographic scale. This involves the integration of a variety of GIS datasets and multiple iterations of expert review and interpretation to delineate the potential wetland areas of Europe. We used the GIS tool ArcGIS9 for analysis. Figure 1 gives an overview of the Swedi (Spatial wetland distribution) model structure and its core input data.

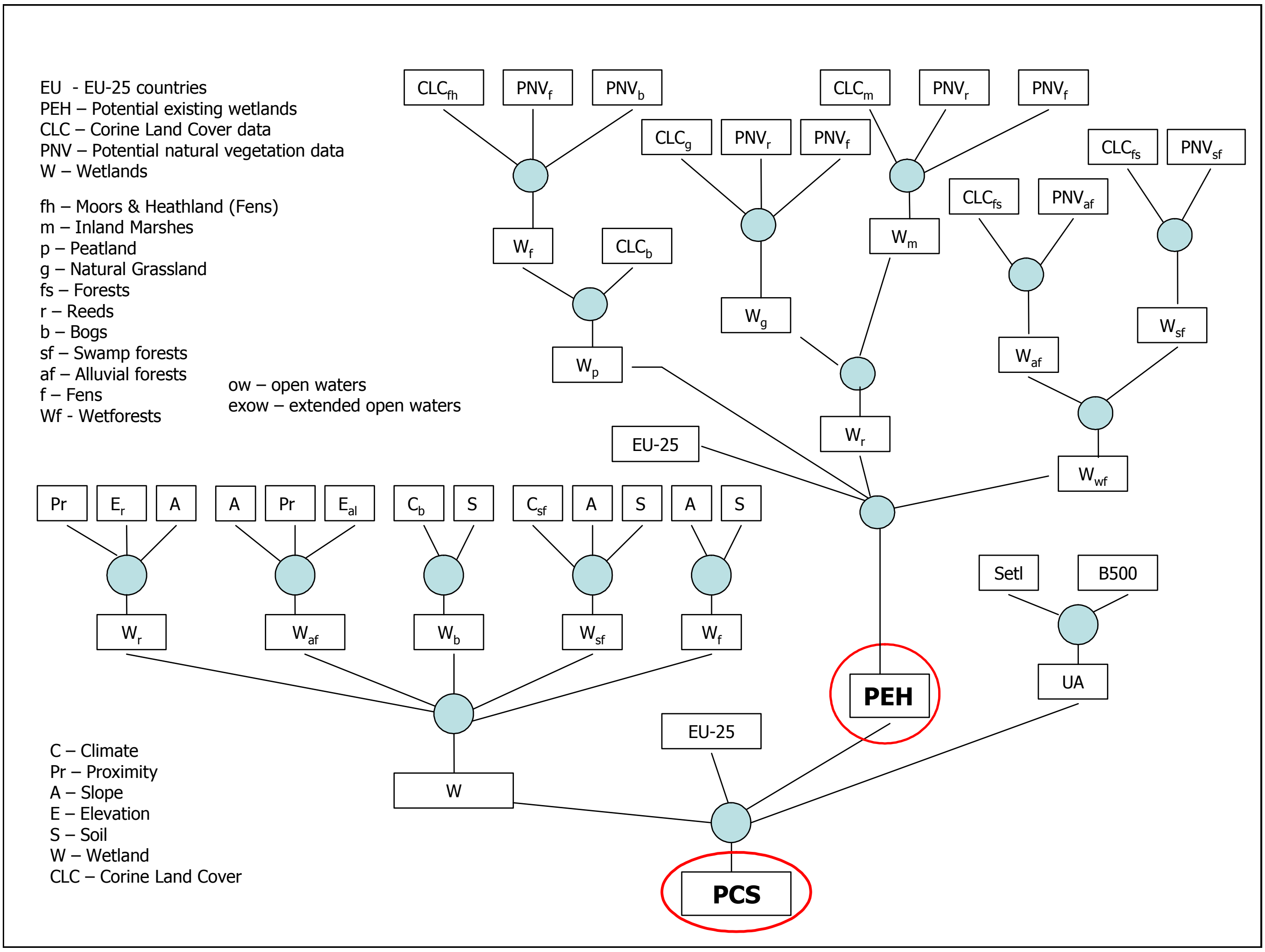

Fig. 1. The spatial wetland distribution model “Swedi”

Results

The results of the Swedi model are illustrated through wetland distribution maps. It is possible to produce the potential existing habitats at spatial resolution of one hectare and the potential convertible sites at 1 km² grid for the EU-25 states excluding the islands Malta and Cyprus. Figure 2 shows the spatial distribution of potential existing habitats and potential convertible sites.

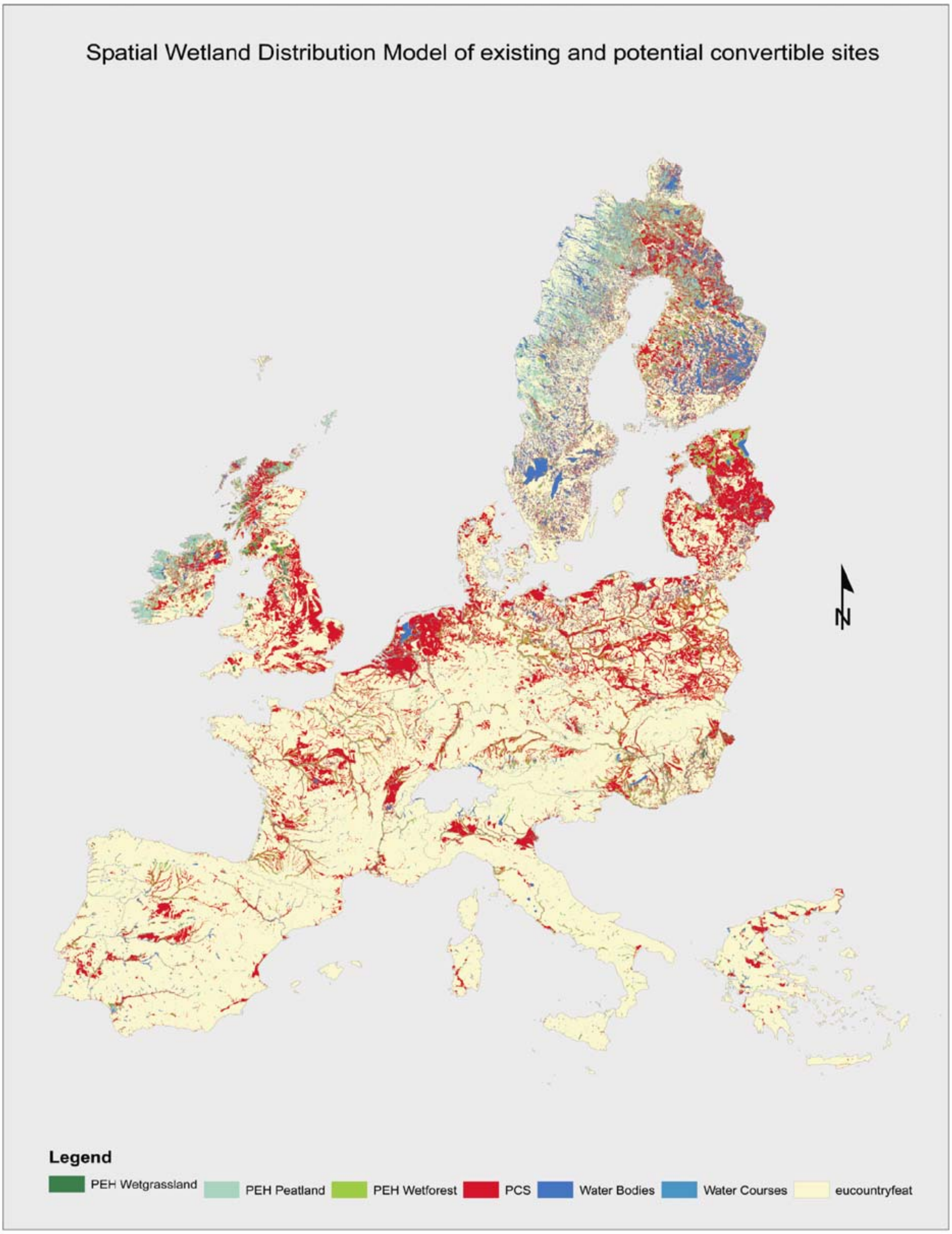

Fig. 2. Map of the spatial distribution of existing habitats and potential wetland restoration sites

Figure 3 gives an overview of the total area (in 1 000 ha) of potential existing and the potential convertible wetland sites per country. Open waters are excluded from the evaluation. Finland and Sweden own by far the most extending existing wetland areas with about 3.8 million ha wetlands. Also Ireland has great amounts of existing wetland areas (about 1.3 million hectares) but less in comparison to the Scandinavian countries. Finland and Sweden also lead in the amount of potential convertible wetland sites. In this category Poland, Great Britain as well as France and to a certain extent Germany as well show high amounts of land suitable for wetland restoration.

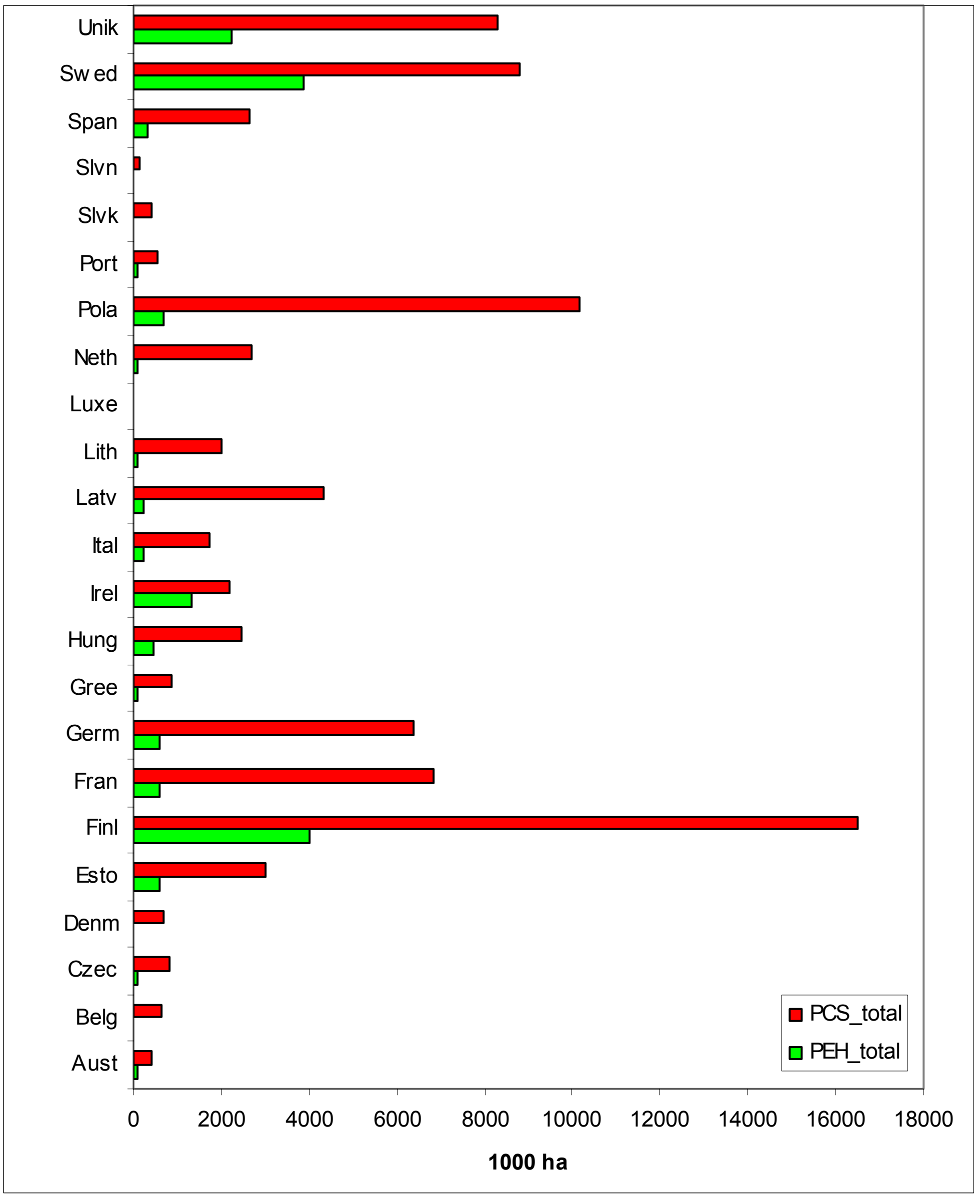

Fig. 3. Total wetland area (in 1000 ha) per country

If we now look at the relationship between wetland areas and country size (see Figure 4) we get a different picture: Now Ireland shows the highest wetland rate (PEH) with about 19% of its country area, followed by Estonia (13%) and Finland (12%). Concerning the PCS per country area, Latvia (68%), the Netherlands (75.6%), and Estonia (66%) have the highest relative potentials. The PCS rate of Finland, Poland, Great Britain, and Ireland amounts to between 31 and 49% per country area. In this case Denmark, Sweden and Germany have potentials of about 16 to 20% and the PCS rate of all other countries amount between 5.1% as lowest rate in Austria and 12.5% in France.

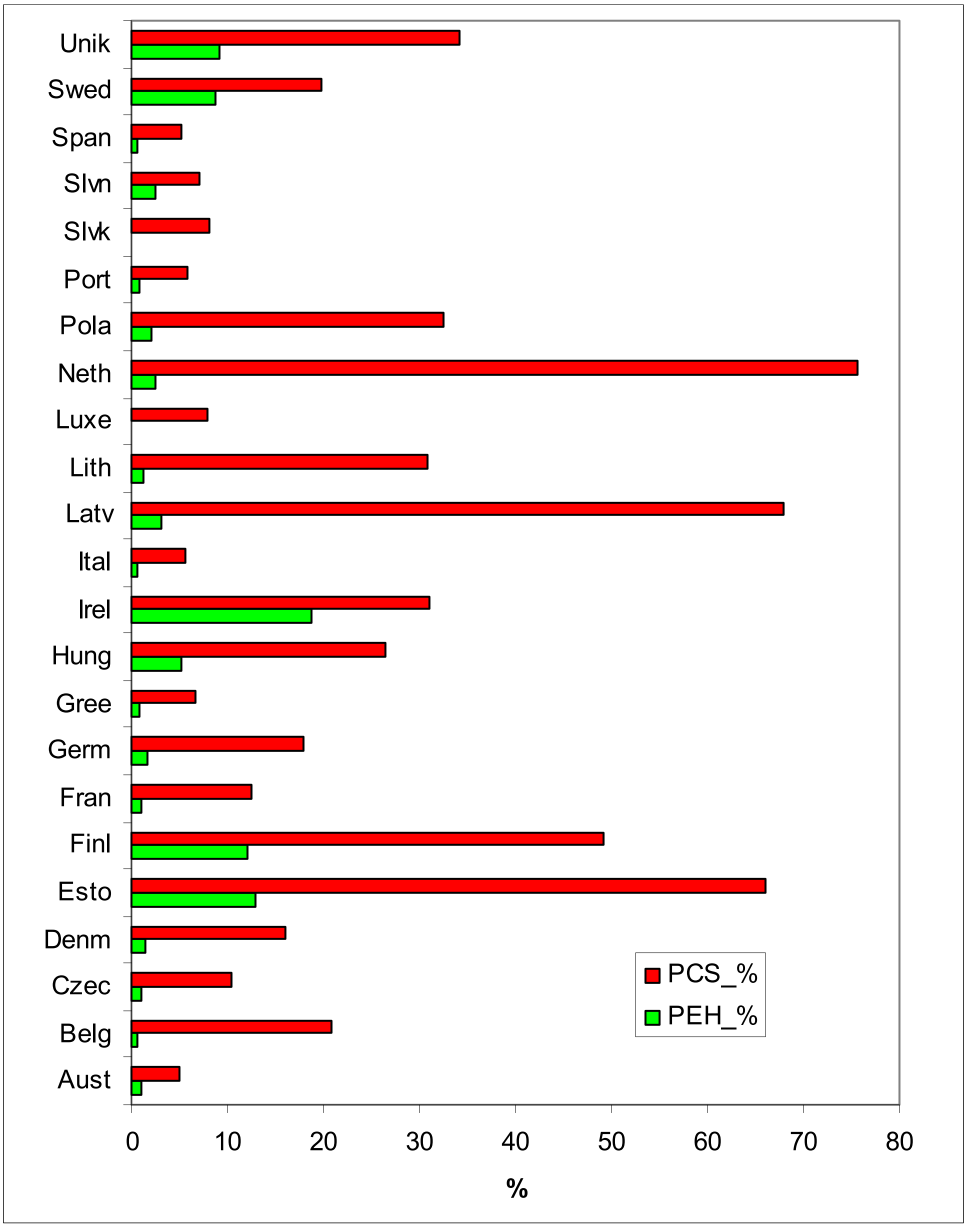

Fig. 4. Relation between country size and wetland area (%)

Discussion

Despite numerous data on land use in Europe, a detailed analysis of the distribution of wetlands and potential restoration sites has been lacking so far. There is a growing demand of policy makers and researchers for high-accuracy landscape information at the European level. We developed a detailed wetland distribution map in European scale with high spatial resolution. Not only does it distinguish between different wetland types but also between potential existing and potential convertible wetland sites. Whereas the evaluation of existing wetlands relies on a cross-compilation of existing spatial datasets, the potential wetland restoration sites are determined by definition of flexible knowledge rules in combination with geographical data. The orientation towards physical parameters and the allowance of overlapping wetland types characterizes the Swedi model. The detailed spatially explicit wetland classification of the Swedi model allows connections to other habitat databases, for example EUNIS, as well.

The accuracy of the Swedi model is strongly restricted by the availability and quality of geographical data. For example, the soil information is generally poor and often misleading from the standpoint of wetland functionality. Another uncertainty is the state of the ecosystem of the PEH. In Swedi we are not able to make statements about the naturalness of the site. Nevertheless, the validation with independent datasets of wetland biotopes proved high accuracy of the existing wetland sites in the Swedi model and the area sizes are mainly reproduced within the uncertainty range. The utilization of GIS makes the methodology applicable and easily to improve concerning data sources.

The knowledge of the extent and distribution of wetlands is important for a variety of applications. It is of utmost importance to provide accurate base data for the management and planning of conservation areas. This study applies an empirical distribution model to wetland ecosystems in European scale. The Swedi model on the other hand is meant to be integrated into the economic optimization EUFASOM model (Schneider et al. 2008) to evaluate the economic wetland potentials per EU-country (Schleupner & Schneider 2008a); furthermore it is going to be the base for biodiversity studies of endangered wetland species (see below) and is used as basis for a cost-effective spatial wetland site-selection model (cf. Schleupner & Schneider 2008b).

B Impact of spatially explicit wetland data on results of a habitat allocation model

Introduction

On the densely populated European continent, competition for land is high. Agricultural and forestry land use lead to habitat loss, degradation, and fragmentation. These are the most important threat factors for biodiversity.

Considering land scarcity and demand for alternative uses, efficiency in biodiversity conservation strongly depends on the efficiency in land allocation. Systematic conservation planning provides tools to identify optimally located priority areas for conservation (Margules and Pressey 2000, Possingham et al. 2000).

The applied model allocates species habitats by minimizing the costs for setting aside land for conservation purposes. We compare two different versions of the model. In the non-GEOSS version there are no restrictions on the available habitat area per planning unit, in the GEOSS version we include explicit modelled wetland habitat data.

Methods

We employ a deterministic, spatially explicit mathematical optimization model programmed in General Algebraic Modelling System (GAMS). It is solved with mixed integer programming.

We apply the minimum set problem from systematic conservation planning. Its objective is to minimize resources expended, subject to the constraint that all biodiversity features meet their conservation objectives (Possingham et al. 2000, McDonnell et al. 2002). Conservation objectives account for the two principal conditions of systematic conservation planning: representation and persistence of the biodiversity features (Margules & Pressey 2000, Sarkar et al. 2006).

The objective function minimizes opportunity cost. Opportunity costs are treated exogenously, they do not change during the model runs. The cost minimization is subject to ecological and spatial constraints. Ecological restrictions ensure that each biodiversity feature reaches a given representation target, meets its area requirements for viable populations, and is allocated to its necessary habitat types. Spatial restrictions ensure that the available habitat areas per planning unit is not exceeded and consider the spatial arrangement of the planning units.

The model is applied to European wetland species. 69 wetland vertebrate species of European conservation concern serve as surrogates for biodiversity. Vertebrate species are common surrogates for biodiversity as there are good occurrence data available and they usually have greater area demands than invertebrates, plant species, and even most ecosystems. The species are derived from the two European directives in relation to wildlife and nature conservation: the Birds and the Habitats Directive (79/409/EEC, 92/43/EEC).

As input to the model we use three types of data where the spatial resolution is of relevance:

- species occurrence data
- habitat areas
- land opportunity costs

Species occurrence data have a resolution of about 50 x 50 km (atlas data originate from Gasc et al. 1997, Hagemeijer and Blair 1997, Mitchell-Jones et al. 1999). The model is based on planning units derived from the species occurrence data. Spatially, the model encompasses the European Union 25, resulting in 2016 planning units.

For the habitat areas, two different procedures are applied. In the non-GEOSS version there are no restrictions on the available habitat area per planning unit, whereas in the GEOSS version we include explicit modelled high resolution wetland habitat data (see report chapter A).

Land opportunity costs differ between countries (agricultural land costs are derived from Eurostat and Farm Accountancy Data Network (FADN) data). For a detailed description of model and input data see Jantke & Schneider (2008).

Results

The model is solved for representation targets 1 to 10 and the two different versions of representing habitat area data. Figure 1 and 2 show the area allocation to the wetland habitat types as well as the total area from model runs with 69 species. The area is shown in million hectares for representation targets from 1 to 10. Each representation targets ensures that each species has enough land on required habitat types to form at least one viable populations in locations where it actually occurs.

Implementation of detailed habitat area data in the GEOSS-version increases the total area and leads to substantial differences in the habitat type shares. A further habitat type had to be introduced in that version which is important especially for area-demanding species that could otherwise not be represented adequately.

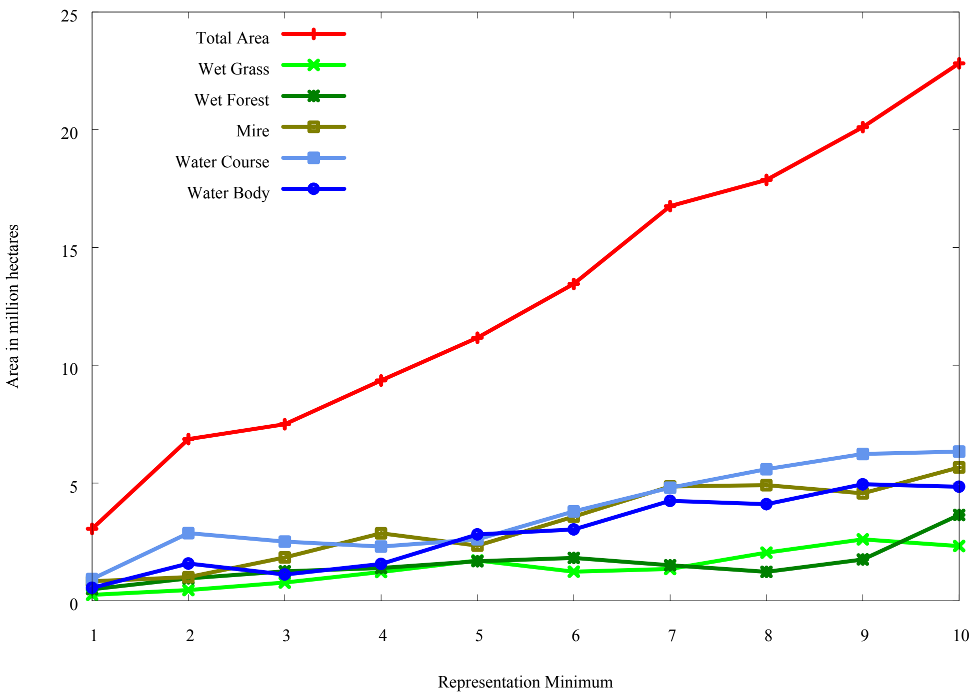

Figure 1: Habitat allocation to habitat types: non-GEOSS version

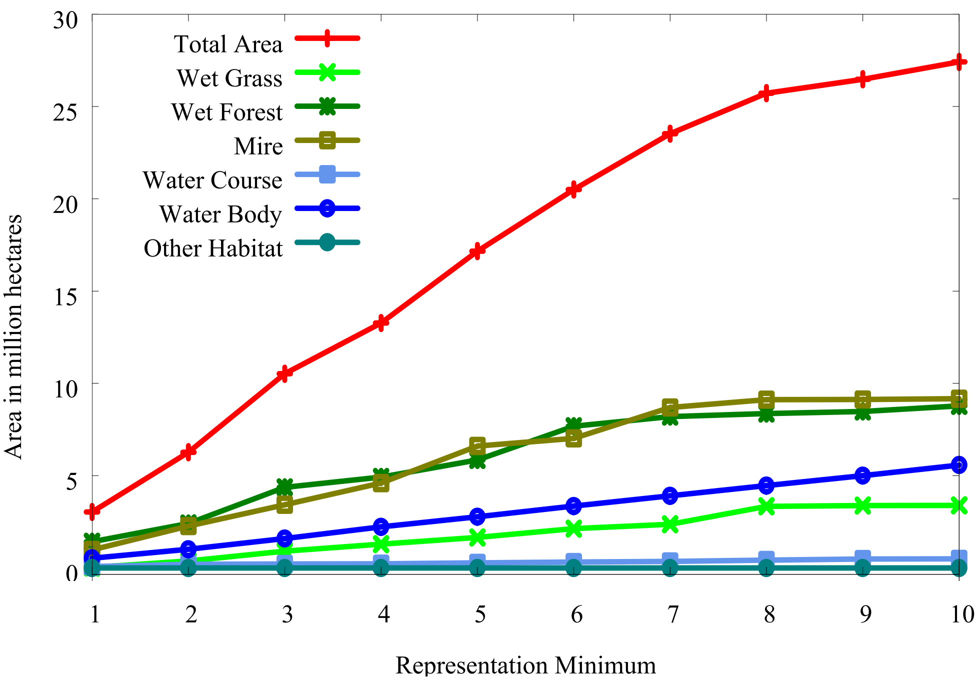

Figure 2: Habitat allocation to habitat types: GEOSS version

Figure 3 displays the opportunity costs for achieving the land needed for habitat protection. The non-GEOSS model version underestimates the costs substantially.

Figures 4 and 5 show the allocation of the total habitat area to the European Union 25 countries. In both versions, most of the habitat is allocated to the five countries Latvia, Lithuania, Estonia, Poland, and Slovenia. The non-GEOSS model version overestimates the available habitat area in Latvia, Lithuania and Estonia. To reach the conservation objectives, the GEOSS version allocates more habitat area in Poland.

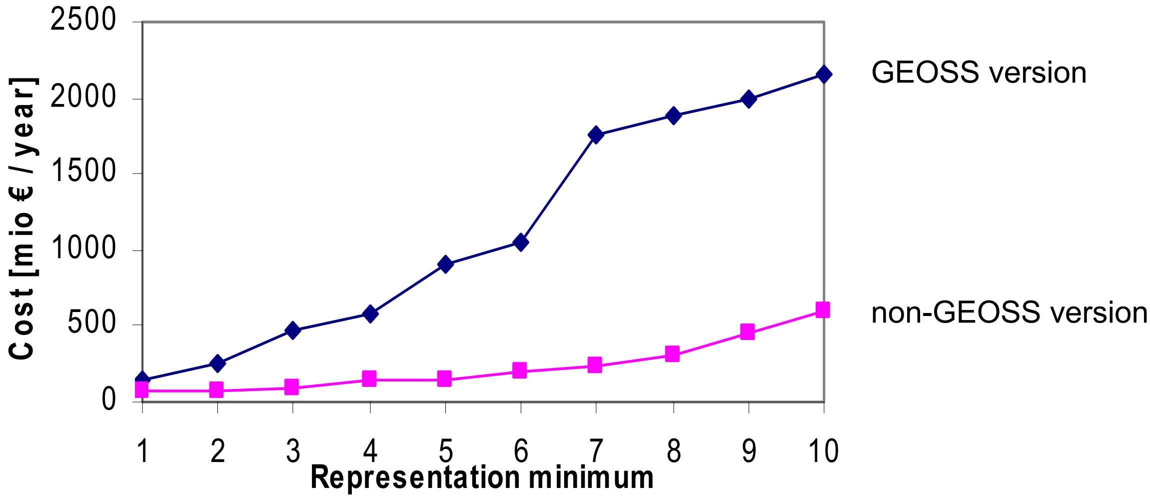

Figure 3: Opportunity costs of habitat protection

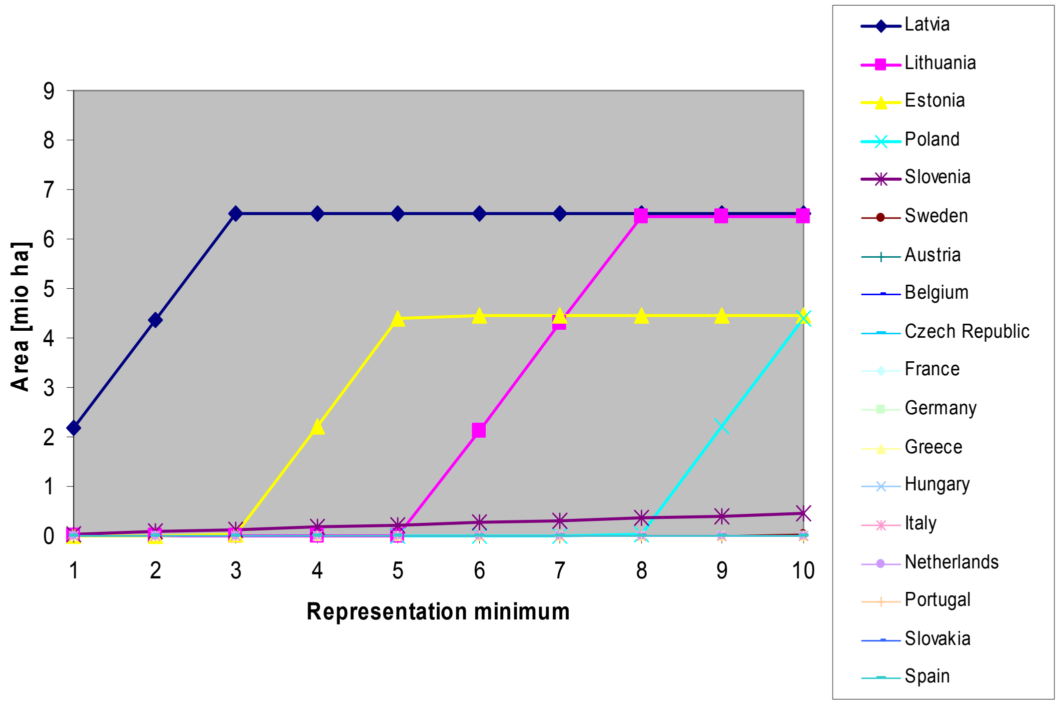

Figure 4: Allocation of habitats to EU25 countries: non-GEOSS version

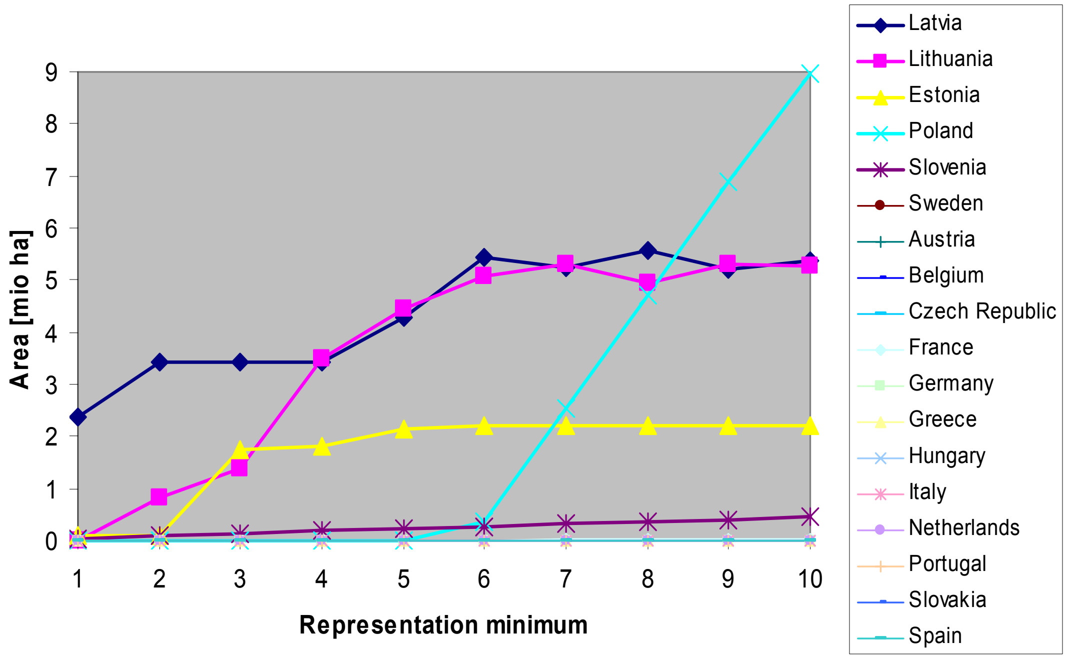

Figure 5: Allocation of habitats to EU25 countries: GEOSS version

Conclusions and Outlook

Conservation planning tools benefit from the integration of high resolution habitat area data. They enable more reliable estimations on area requirements, habitat shares and the opportunity costs of habitat protection. Especially the costs of habitat protection were severely underestimated in our non-GEOSS model version.

We plan to implement opportunity costs on homogenous response units (HRU) (see Skalský et al. 2007 for details) level which will further improve the model accuracy.

Comprehensive species occurrence data with a higher resolution are not available for the spatial scope of the model. Downscaling would therefore be an option to work on smaller scales (see Araujo et al. (2005) for an example on European atlas data).

The spatial wetland distribution model is going to be extended to whole Europe.

Acknowledgements

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References

Araujo, M. B., Thuiller, W., Williams, P. H., & Reginster, I. 2005. Downscaling European species atlas distributions to a finer resolution: implications for conservation planning. Global Ecology and Biogeography 14, 17-30.

Gasc, J. P., Cabela, A., Crnobrnja-Isailovic, J., Dolmen, D., Grossenbacher, K., Haffner, P., Lescure, J., Martens, H., Martínez Rica, J. P., Maurin, H., Oliveira, M. E., Sofiandou, T. S., Veith, M., & Zuiderwijk, A. 1997. *Atlas of amphibians and reptiles in Europe*, Collection Group on Earth Observations 2005, *Global Earth Observation System of Systems GEOSS*, ESA Publications Division, Noordwijk.

Jantke, K. & Schneider, U. A. 2008, *Multiple-species conservation planning with different degrees of coordination: Quantifying area requirements using mixed integer programming*, Research Unit Sustainability and Global Change, Hamburg University.

Patrimoines Naturels edn. Societas Europaea Herpetologica, Muséum National d'Histoire Naturelle & Service du Petrimone Naturel, Paris.

Hagemeijer, W. J. M. & Blair, M. J. 1997. *The EBCC Atlas of European Breeding Birds: Their Distribution and Abundance* T & A D Poyser, London.

Margules, C. R. & Pressey, R. L. 2000. Systematic conservation planning. Nature 405, 243-253.

McDonnell, M. D., Possingham, H. P., Ball, I. R., & Cousins, E. A. 2002. Mathematical methods for spatially cohesive reserve design. Environmental Modeling & Assessment 7, 107-114.

Mitchell-Jones, A. J., Amori, G., Bogdanowicz, W., Krystufek, B., Reijnders, P. J. H., Spitzenberger, F., Stubbe, M., Thissen, J. B. M., Vohralík, V., & Zima, J. 1999. *The Atlas of European Mammals* Academic Press, London.

Possingham, H., Ball, I., & Andelman, S. 2000. Mathematical methods for identifying representative reserve networks. In Quantitative methods for conservation biology, eds. S. Ferson & M. A. Burgman, pp. 291-306. Springer, New York.

Sarkar, S., Pressey, R. L., Faith, D. P., Margules, C. R., Fuller, T., Stoms, D. M., Moffett, A., Wilson, K. A., Williams, K. J., Williams, P. H., & Andelman, S. 2006. Biodiversity conservation planning tools: Present status and challenges for the future. Annual Review of Environment and Resources 31, 123-159.

Schleupner, C. and U.A. Schneider (2008a), *A cost-efficient spatial wetland site-selection model for European biotope restoration*, **FNU-159**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg.

Schleupner, C. and U.A. Schneider (2008b), *Evaluation of European wetland restoration potentials by considering economic costs under different policy options*, **FNU-158**, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg.

Schneider UA, Balkovic J, De Cara S, Franklin O, Fritz S, Havlik P, Huck I, Jantke K, Kallio AMI, Kraxner F, Moiseyev A, Obersteiner M, Ramos CI, Schleupner C, Schmid E, Schwab D & Skalsky R (2008) The European Forest and Agricultural Sector Optimization Model – EUFASOM. FNU-156, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg.

Skalský, R., Schmid, E., Tarasovičová, Z., & Balkovič, J. 2007. *Detailed description of the data strategy for global EPIC modelling. The GEO-BENE Database Report. 30.09.2007.*

Effects of bioenergy policies and targets on European wetland restoration options

C. Schleupner and U. A. Schneider

Abstract— The EU is committed to combat climate change and to increase security of its energy supply. Bioenergy from forestry and agriculture plays a key role for both. Also the EU agreed to halt the loss of biodiversity within its member states. To fulfil the biodiversity target more nature conservation and restoration sites need to be designated. There are arising concerns that an increased cultivation of bioenergy crops will decrease the land available for nature reserves and for "traditional" agriculture and forestry. To assess the true role of bioenergy in light of possible negative impacts on ecosystems, the European Forest and Agricultural Sector Optimization Model (EUFASOM) assesses simultaneously economic and environmental aspects of land use. This study contributes to the assessment by analyzing the effect of bioenergy production on European wetland allocations by integrating the spatial wetland distribution model "Swedi" to EUFASOM. This way the costs and benefits of the appropriate measures and its consequences for agriculture and forestry are investigated. One aim is to find the socially optimal balance between alternative wetland uses by integrating biological benefits – in this case wetlands - and economic opportunities – here agriculture and forestry. The analyses of this study offer insights into environmental conservation effects in European scale caused by policy driven land use changes.

***Keywords*—**biomass, conservation planning, land use, leakage.

I. Introduction

To increase security of energy supply and reduce greenhouse gas (GHG) emissions the European Commission set out a long-term strategy for renewable energy in the European Union (EU). Recent bioenergy targets are described for the year 2020 that involve a share of renewable energy of 21% of the total electricity consumption as well as 10% bio-fuels of the total fuel consumption. Bioenergy from forestry and agriculture plays a key role for both. In 2005 the Commission published a detailed biomass action plan concerning its production targets. Consequently, a significant increase of biomass energy plantations has been observed in Europe most recently. There are arising concerns that an increased cultivation of bioenergy crops will decrease the land available for nature reserves and for "traditional" agriculture and forestry.

Europe is densely populated in some parts and without protection and management, agricultural and forest demands would leave space for nature conservation in marginal areas only. Counteracting these problems, several directives at EU-level were established to safeguard biodiversity and valuable natural biotopes. For example, under the *Habitats Directive* the European member states are required to identify and designate Special Protection Areas which are important habitats for the protection of species covered by the directive. Many existing reserves in highly modified human cultural landscapes are too small or too isolated to provide for the full biodiversity benefits. It is therefore necessary to acquire additional land with habitat value or restoration potential [1]. In this respect restoration and conservation management are increasingly viewed as complementary activities and restoration measures are therefore often included in conservation management [2]-[4]. To fulfil the European biodiversity targets more nature conservation and restoration sites need to be designated.

The rising political demand for bioenergy in the context of climate change mitigation policies has posed an additional obstacle to ecosystem preservation and restoration. [5], for example, found very large bioenergy resource potentials for Poland. Bioenergy demands increase the value of land and thus, increase the opportunity costs for protected nature areas. As land rents rise, designing space and property for nature conservation has grown to a critical economic and social issue without ignoring production land uses. Protected areas cannot be sustained in isolation from the economic activities in and around them. It is of importance that humans are considered as part of the environment and not only as the underlying problem [6]. Socio-economic considerations and temporal restrictions limit the realization of a chosen restoration goal for a certain wetland or parts thereof. The evaluation of the socio-political interests also includes cost analyses, because all conservation and restoration options incur costs. However,

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costs have not received much consideration in designs aimed at expanding reserve networks in broader scales [7].

The principle in the presented study is to optimize different land uses to allow for the persistence and reintroduction of ecosystems by considering bio-geophysical as well as socio-economic factors. This way we can demonstrate the tradeoffs between obtaining higher levels of a conservation target and the increase in cost necessary to obtain it. An important research question is also the potential influence of biomass supply on wetland restoration efforts. The analysis of this study has been executed in European scale by using the EU-25 countries, because conservation planning at broad scales can help to identify areas or regions in which the payoff for conservation efforts is likely to be greatest [8]. So far conservationists have mainly focused on finer scales. But there are increasing requests among scientists for embracing and engaging conservation planning at broader spatial scales to obtain a holistic view of the landscape [8]-[10]. It is recommended more and more often that the scale of the goals and objectives must also match the scale of the challenge. This implies that a good deal of conservation action must be directed at the scale of land use and of socio-political interests.

II. Methodology

A. The Spatial Wetland Distribution (Swedi) model

This study focuses on inland freshwater wetlands of Europe. Within the EU directives wetland habitats receive a special status. While fens and floodplain forests have been drained and cleared since early medieval times, the main decrease in wetlands happened over the last century and is still continuing [11]. Ongoing drainage, conversion, pollution, and over-exploitation of the wetland resources make them to be among the world's most threatened ecosystems [12]. The last decades have seen increasing interest not only in wetland conservation but also in the restoration of wetlands. In this study we use wetland restoration as generic term. This includes both the improvement in degraded wetlands, and re-creation on sites where similar habitat formerly occurred as well as wetland creation in areas where wetlands are established for the first time - within historical time span [13].

Before evaluating the economic wetland potentials the total wetland area per country needs to be determined. Because of missing base data a methodology to identify wetland distributions including their area potentials has been developed. This resulted in the Swedi model [14]. The Swedi model estimates the spatial distribution of European wetlands by distinguishing between existing wetlands and wetland restoration sites. Five wetland types (bog, fen, alluvial forest, swamp forest, wet grassland) are differentiated. Swedi is a GIS-based model that relies on multiple spatial relationships. It covers the whole EU-25 area excluding Malta and Cyprus at resolution of 1 km². The model also differentiates between six wetland size classes, and assesses the restoration success of a potential wetland restoration site after area quality and potential natural wetland vegetation [15]. The results of the Swedi model were aggregated to country level by maintaining their accuracy in details.

B. EUFASOM Scenarios

We used the European Forest and Agricultural Sector Optimization Model (EUFASOM) [16] to compute the competitive economic potential of wetlands. EUFASOM is a dynamic, partial equilibrium model of the European Agricultural and Forestry sector, which has been developed to analyze economic and environmental impacts of changing policies, technologies, resources, and markets [16]. Land management choices link land, labour, water, forests, animal herds, and other resources to food, fibre, timber, and bioenergy production and their markets. The land management choices include explicitly all major arable and dedicated energy crops, all major livestock categories, more than twenty tree species and forest types, and alternative management systems regarding soil tillage, irrigation, crop fertilization, animal feeding and manure management, and forest thinning.

The geographically explicit resolution of EUFASOM involves member states within EU-25 plus eleven international regions which cover the entire earth. For each EU member state, additional spatial variation can be integrated implicitly via area shares. These differences include a) natural variations pertaining to altitude, soil texture, and slope, b) variations in the state of land and forests pertaining to soil organic carbon levels, forest type, and forest age and c) variations in enterprise structure pertaining to farm size and farming type. However, current computational restrictions do not allow a simultaneous representation of all the above listed differences. The temporal resolution of EUFASOM comprises 5-year periods starting with the 2005-2010 period and terminating anywhere between 2005-2010 and 2145-2150. Exogenous data on state and endowment of resources, land management options and processing technologies, commodity demand, and policies can be adjusted for each period to reflect different development scenarios.

EUFASOM is a large mathematical programming model, which maximizes the discounted sum across regions and time periods of consumer surplus from all final commodity markets plus producer surplus from all price-endogenous resources minus costs for production and commodity trade plus terminal values of standing forests plus benefits from subsidies minus costs from taxes. Restrictions depict resource qualities and endowments, technical efficiencies, crop rotation constraints, environmental impact accounts, political quotas, and intertemporal relationships for forest inventories, soil organic matter levels, dead wood pools, and timber commodity stocks. The non-linear objective function terms are stepwise approximated to allow EUFASOM to be solved as linear program. Each individual model solution yields optimal levels for all endogenous variables and shadow prices for all constraints. Particularly, production, consumption, and trade variables determine land use and land use change, resource deployment, environmental impacts, and supply, demand, and trade of agricultural and forest commodities. Shadow prices on supply demand balances for resources and commodities identify resource values and market clearing prices for commodities, respectively. Shadow prices on environmental targets reveal the marginal costs of achieving them.

For this study, we extended EUFASOM by integrating the spatially explicit wetland distribution data from SWEDI. We aggregated all spatial units within each EU member state but preserved habitat type, size, and suitability classifications. In addition, we assumed conversion and maintenance costs coefficients for all wetland restoration efforts. To assess the economic potential and agricultural impacts of wetland protection efforts, we specified different scenarios. In particular, we distinguished a) joint vs. country specific wetland targets, b) protected vs. unprotected status of existing wetlands, c) size dependent vs. suitability dependent representation of SWEDI data in EUFASOM, d) wetland targets with vs. without simultaneous European bioenergy target, and e) 20 different wetland targets covering the whole range from no protection to maximum protection. Each selected combination of these scenario assumptions corresponds to a separate solution of EUFASOM.

III. Empirical Results

Through EUFASOM scenarios economic and environmental impacts of changing policies, technologies, resources, and markets are analysed to find the socially optimal land use allocation. By including the wetland data of SWEDI into EUFASOM the economic potentials of wetlands, its effects on agricultural and forestry markets, and environmental impacts of wetland protection/restoration efforts are determined for different policy scenarios concerning biomass production. Figure 1 shows the economic and technical potential of wetlands of the EU-25 region.

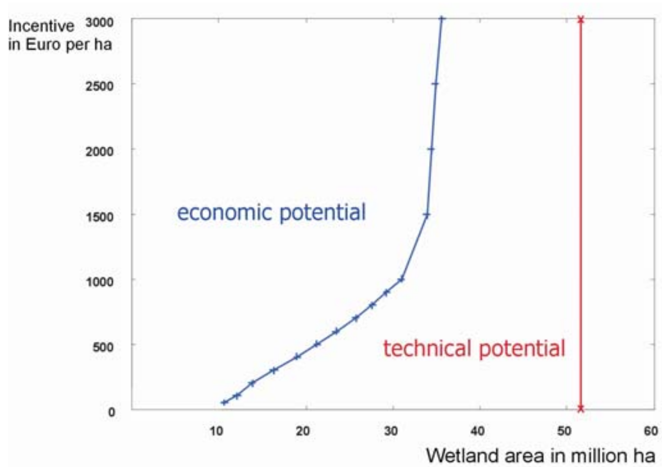


Fig. 1 Economic versus technical potential of protected wetlands in EU25

The right curve illustrates the maximum technical potential of wetland area in Europe. In other words, the technical wetland potential is the summed area of existing wetlands and the conversion sites. Generally, it applies that the more wetland is restored the more expensive the conversion costs become because the marginal costs, i.e. opportunity costs, rise. We included 20 different wetland targets from no protection to maximum protection expressed through incentives in Euro per hectare converted wetland area. The use of incentive pricing in nature conservation is commonly used. The comparison of economic potential with the technical potential shows that from a certain point on - in this case at incentives of about 1 500 €/ha - additional wetland conversion gets economically unfeasible. As a consequence, the technical potential outreaches the economic potential. Also the amount of incentives outreaching 1000 Euro per hectare is far from realistic but shows well the model performance.

The relationship between incentives and available wetland area for conservation is then considered for each country specifically or combined for all EU-25 states as shown in figure 2.

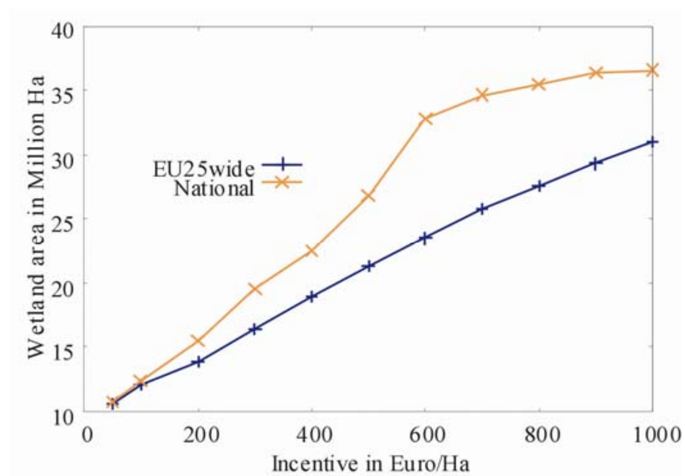


Fig. 2 Country specific versus joint wetland targets for no biomass target expressed in million wet tons of biomass

The upper curve depicts the national scenarios. Here, we assume implementation of wetland conservation targets in one EU-country only whereas all other countries do not adopt these targets. This scenario is conducted for each country separately and by adding up all national scenarios we achieve the artificial leakage curve as shown in the figure. At EU-25 wide scenarios all countries have the same wetland targets. This leakage phenomenon reflects in the differences of the national and EU-25 wide curves in the way that the national scenarios supply more potential wetland area at all incentives than the EU-25 wide scenarios. This means, that on the one hand wetland conservation without overall conservation targets is cheaper, but on the other hand that wetland restoration targets in one country stimulate agricultural production in other countries due to market linkages. In the EU-25 scenarios land competition rises equally for every member state and therefore land prices rise as well as the price for wetland conservation options on agricultural and forested land.

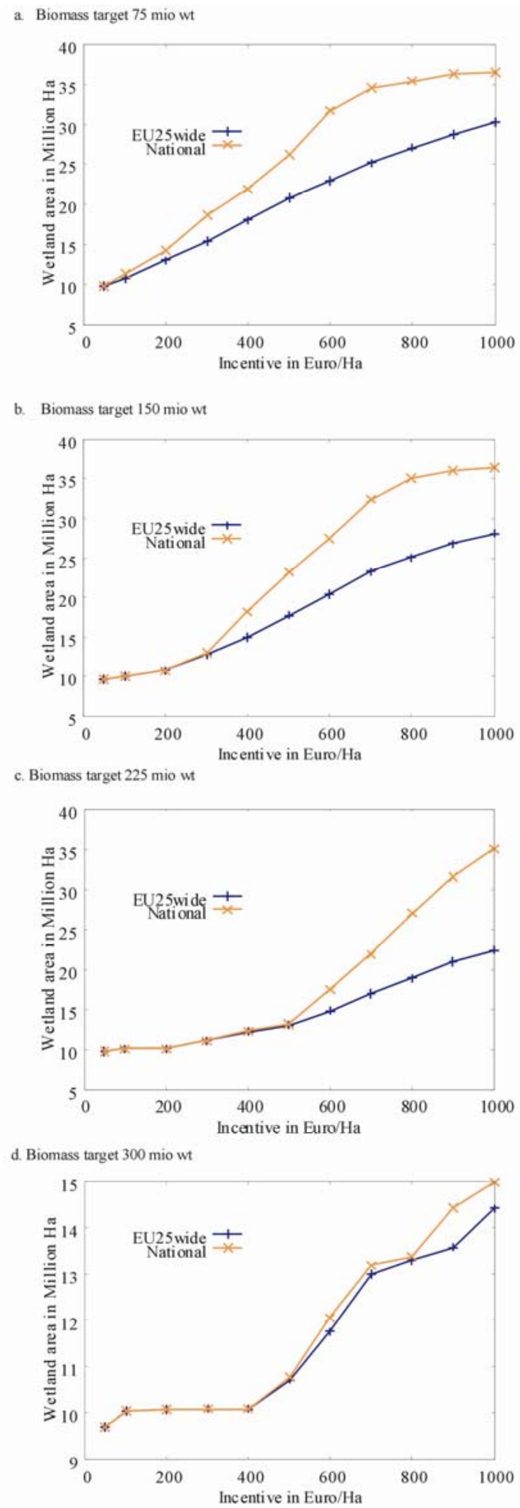


Fig. 3 Country specific versus joint wetland targets for different biomass targets expressed in million wet tons of biomass

The curves of figure 2 explain scenarios without any biomass targets. To evaluate potential impacts of biomass production on the allocation of suitable wetland sites the national and joint scenarios are applied for different biomass targets (figure 3). The European Union described bioenergy targets for the year 2020 that involves a share of renewable energy of 21% of the total electricity consumption as well as 10% bio-fuels of the total fuel consumption. This target can be fulfilled by a supply of about 300 mio. wet tons of biomass.

The scenarios of figure 3 differentiate the fulfilment of this target to 25 (a), 50 (b), 75 (c), and 100% (d). Comparing the national with the EU-25 wide scenarios under consideration of the biomass targets one observes not only a decline in wetland area allocation. Also the national curve reconciles to the EU-25 wide curve the higher the biomass target is set by starting at lower incentives. At biomass target of 100% both curves almost align because the national wetland targets are outweighed by the biomass targets. Consequently, the inclusion of a third component, the biomass targets, into the model resulted in a reduction of the accounting error caused by the national scenarios. The land use competition and the gain of more profits from land utilization under biomass plantation than under wetland conservation, respectively restoration, play a major role for these results.

The same scenarios are applied under consideration of food price development. At figure 4 food prices, expressed through the Fisher Index, were integrated into the analysis.

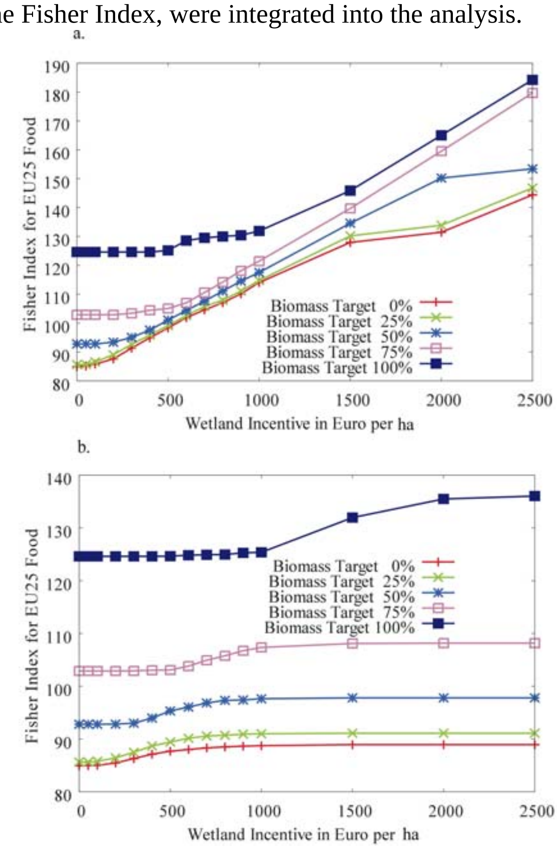


Fig. 4 EU-25 wide (a) and national (b) scenarios analysing food prices of the EU-25 states in relation to wetland restoration incentives

Shown are scenarios without wetland protection. In the case, where the food prices fall below 100, unprotected wetland area is converted into agricultural utilization. The curves show also a dependency on wetland incentives, whereas the "national" scenarios result in lower food prices than the EU25 wide scenarios, because of leakage. Also comparisons of different biomass targets show the influence of land competition: The lower the biomass targets the lower are also the food prices due to less competition in utilization demands. The national scenarios with a biomass target of 100% keep clear distance to the other national targets, but show in comparison to the EU-25 wide scenarios hardly a rise in prices even at higher incentives. Again, the leakage factor is visible. At the national scenarios additionally needed food is imported from other countries without wetland targets, whereas at the EU-25 wide scenarios economic costs rise due to competing utilization demands between traditional agriculture, bioenergy plantations and wetland targets. In these scenarios prices for food are higher.

EU-25 wide scenarios with joint incentives for all EU-countries are used for the following scenarios. Figure 5 distinguishes between protected (a.) versus unprotected status of existing wetlands (b.).

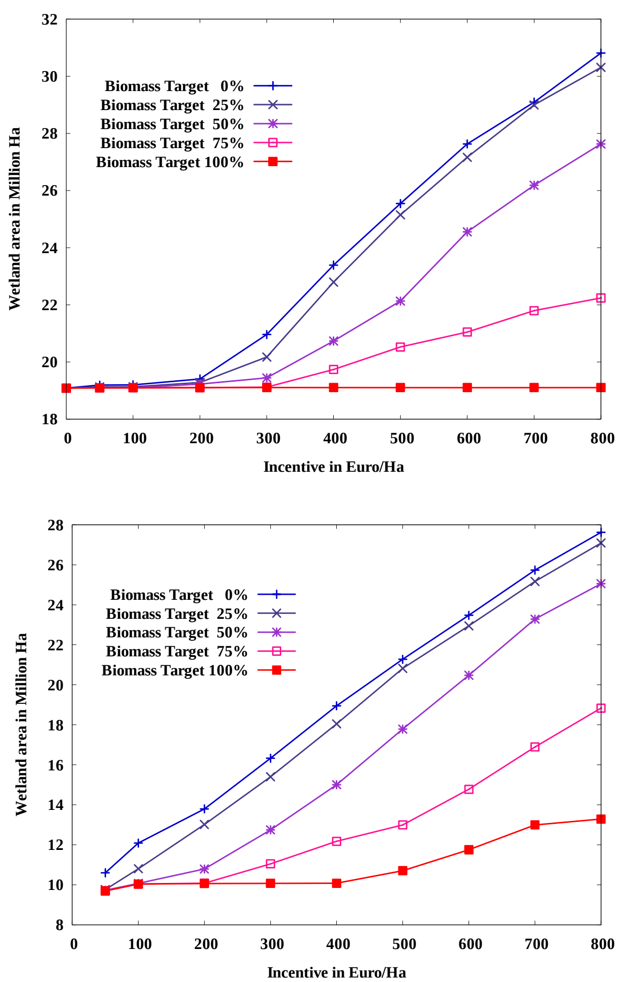


Fig. 5 Protected (a) versus unprotected (b) status of existing wetlands for different biomass targets

The protection of existing wetlands implies that these wetlands are not available to be used as agricultural fields or forests, for example, whereas at unprotected status these wetlands may be used for other utilizations as well (cf. figure 4). The curves show clear differences also due to different values at the beginning. The scenario with unprotected existing wetlands indicates a more intense rise of wetland area at low incentives, but it also starts at small wetland area in comparison to the protected status, where a rise in wetland area is initiated only from incentives of 200 €/ha. At biomass target 100 even no rise happens at all. The protection-scenarios therefore imply that if wetlands would not be protected, most of the biotopes would be converted into other utilization. Only at incentives of about 400 €/ha the wetland area at scenarios without biomass target reaches the starting point of existing wetland area at protected status.

The EUFASOM scenarios in figures 3 to 5 show the integration of bioenergy targets with realisation of 25, 50, 75 and 100 % as well as without such target. The results show that in all scenarios biomass targets for climate change mitigation have enormous effects on wetland conservation and restoration. In the following we are going to use the scenarios of figure 2 and 3 for a more detailed analysis. In this case we chose the EU-25 wide curves of wetland area potentials without biomass target (Fig 2.) and with biomass target 100% (Fig. 3 e). We show exemplarily for both cases the wetland potentials for each country separately at incentives of 0, 1000, and 3000 €/ha. Figure 6 represents maps of the total potential wetland area per country.

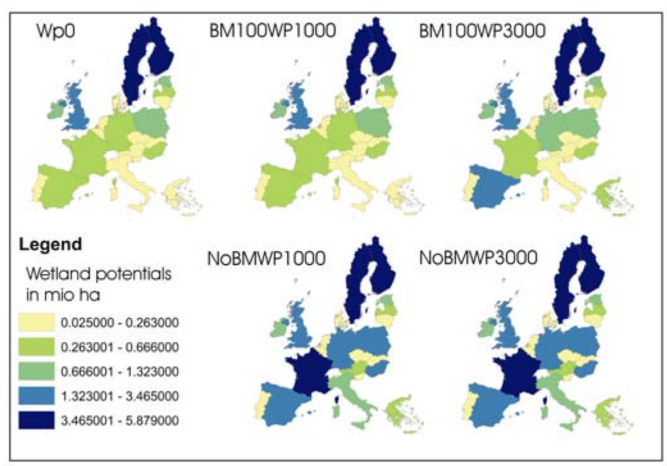


Fig. 6 Total potential wetland area per country at incentives of 0, 1000, and 3000 €/ha (WP) with (BM100) and without biomass target 100% (NoBM)

It illustrates great wetland potentials at the starting point in Sweden, Finland, but also in the United Kingdom. At this stage the total wetland potentials in Ireland, Poland as well as in Estland are also remarkable, whereas other countries like Italy, Greece, but also Denmark or the Netherlands only have minor total wetland potentials. Comparing now the wetland potentials per country at incentives of 1000 Euro per hectare with and without biomass target one gets only one another picture: The wetland potentials remain stable with biomass target 100%, but the wetland potentials without biomass target show most extending rise in wetland area in France, but also the wetlands in Spain, Germany and Hungary grew as well as wetland areas in Austria, Italy and Greece increased.

Even if an increase in wetland area took place as figure 7 illustrates are the changes in wetland potentials not visible on the map. Therefore shows the map at incentives of 3000 Euro per hectare no differences to the scenarios of 1000 Euro per hectare incentives without biomass target. On the other hand are at the stage of 3000 Euro per hectare increasing wetland potentials at scenarios with inclusion of biomass target 100% visible. In these cases the wetland areas of Spain, Germany and Greece rise considerably.

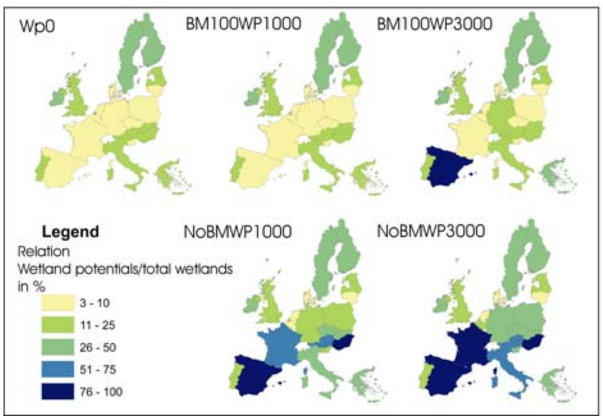


Fig. 7 Relation of potential wetland area to the maximum wetland area per country in percent with incentives of 0, 1000, and 3000 €/ha with and without biomass target 100%

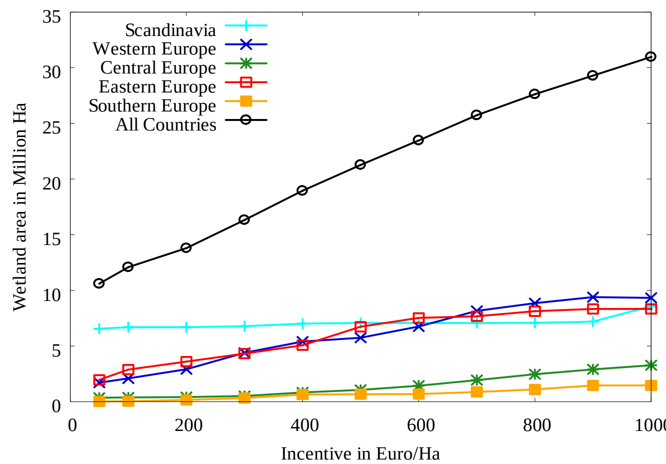
In contrast to figure 6 illustrates figure 7 the share of the respective wetland area in relation to the maximum wetland area in percent depending on the EUFASOM scenarios explained through maps. In comparison to the results of figure 6, France, Poland and Germany only own minor shares of their total wetland potentials at the starting point, whereas now Italy, Greece, Austria, Slovakia and also Portugal have higher relative wetland area compared to their total wetland area. The maps change drastically at the 1000 Euro incentive without biomass targets where besides the above mentioned countries also the Czech Republic shows rising wetland potentials. The results of the 3000 Euro incentives without biomass target indicate that the share of wetland potentials to the total potential wetland area of France, Germany, Poland and Italy increased more than in other countries. The high shares of 76 to 100% of Spain or France, for example, results from relatively small total wetland potentials of that country.

To learn more about regional differences we aggregated the data of the potential wetland areas into regions (Table 2).

Figure 8 illustrates these differences in more detail by comparing scenarios with biomass target 100% and without biomass target.

TABLE I
DEFINITION OF EU-25 REGIONS

Region	Country
Scand	Finland, Sweden
East	Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia
Central	Austria, Belgium, Czech Rep., Denmark, Luxembourg, Netherlands
West	France, Ireland, Portugal, Spain, UK
South	Greece, Slovenia, Italy



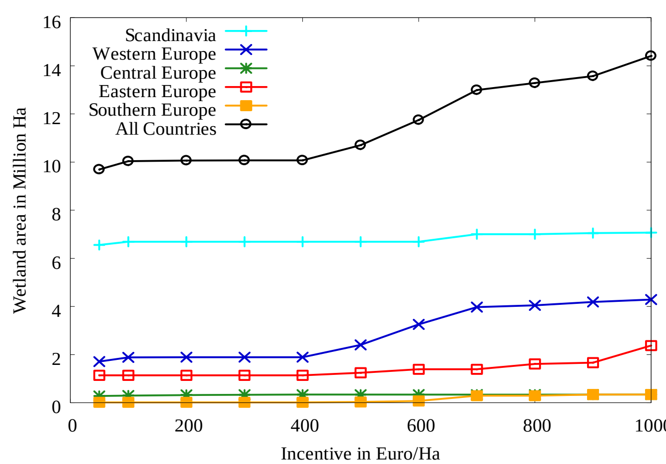


Fig. 8 Regional distribution of unprotected wetlands for a. biomass target 100% and b. Biomass target 0

The wetland area in the Scandinavian Region keeps nearly constant independent of biomass targets. By far the most extending wetland increase is observed in Western European where the wetland area even raises above the Scandinavian wetland potentials at the scenario without biomass target. Here, also the Eastern European region shows extending growth in wetland area similar to the Western European region. This is not the case at scenarios with biomass targets. The Central and South European regions show an increase in wetland area only at scenarios without biomass targets. In relation to their low total wetland potentials due to geo-ecological factors the share in rise of wetland area can be even rated higher than elsewhere in this case.

IV. Summary and Conclusions

The GIS-based Swedi model estimates the spatially explicit distribution of existing and potential wetlands. Results show not only a heterogeneous distribution across countries but also large differences between the two areas. Potential wetland areas in Europe are about five times larger than existing wetlands. To evaluate the competitive economic potential of wetland preservation under different policy options, Swedi data were aggregated and integrated into EUFASOM. This bottom-up, partial equilibrium model portrays the competition for scarce land between agriculture, forestry, dedicated bioenergy enterprises, and nature reserves. Production intensities, prices, international trade, and demand for agricultural and forest commodities are endogenous. As shown in chapter 3, the spatial extent of wetland preservation is sensitive to incentives. It is relatively inexpensive to achieve moderate levels of conservation but marginal cost rise steadily as the total protected areas increase [17]-[19]. Note that incentives of several thousand Euro per hectare are easy to simulate with a mathematical programming model but difficult to realize politically.

Wetland targets in one place stimulate land use intensification elsewhere due to market linkages. Thus when wetland restoration in one country reduces agricultural production the market is likely to cause this to be offset by increased production elsewhere [20]. This leakage phenomenon indicates also that environmental stresses, in this case to wetlands, may be transferred to other countries [21]. However, we find that wetland conversion rises when a national rather than an EU-25 wide perspective is employed. On the other hand reduces the introduction of biomass targets the bias between national and EU-25 wide perspectives due to additional land utilization demands.

Large wetland areas impact food production, consumption, and market prices. Higher food prices rise the opportunity costs of wetlands. If these cost changes are ignored, the resulting marginal cost predictions can be substantially underestimated. Similarly, adding nationally obtained cost estimates understates the true cost of EU-wide preservation incentives. In independent national assessments, costs appear lower because agricultural cost changes from simultaneous preservation policies in other countries are neglected.

Existing European wetlands are relatively well protected through EU-policy measures. However, these areas may need to be extended to realize the ambitious political targets related to biodiversity protection.

Bioenergy targets have enormous effects on conservation planning and nature conservation. An enforcement to achieve the EU-bioenergy target, meaning to produce about 300 mio wet tons of biomass per year, would lead to less wetland restoration areas at very high incentives, but even to no additional wetlands, respectively conservation areas, than the existing at incentives up to 1000 Euro per hectare. This also reflects in regional and country-specific analyses.

Regional and country-specific differences in wetland potentials exist as well. The wetlands are not evenly distributed due to their geo-ecological and spatial relationships but also because of economic aspects like land costs, for example.

The presented study helps to find the socially optimal balance between alternative wetland uses by integrating biological benefits – in this case wetlands - and economic opportunities – here agriculture and forestry. The analyses offer insights into environmental conservation effects in European scale caused by policy driven land use changes. Spatial data provide a possibility to build the interface between economic and ecologic models.

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References

[1] J. R. Miller, "Habitat and Landscape Design: Concepts, Constraints and Opportunities," in: *Managing and Designing Landscapes for Conservation: Moving from Perspectives to Principles,* D. B. Lindenmayer and R.J. Hobbs, Eds. Conservation Science and Practice Series 1, Oxford: Blackwell Publishing, 2007, pp. 81-95.

[2] T. P. Young, "Restoration ecology and conservation biology," *Biological Conservation*, vol. 92, pp.73-83, 2000.

[3] R. J. Hobbs, "Restoration ecology and landscape ecology," in: *Issues and Perspectives in Landscape Ecology,* J. A. Wiens and M. R. Moss, Eds. Cambridge: Cambridge University Press, 2005, pp. 217-229.

[4] A. D. Manning, "Ecosystems, Ecosystem Processes and Global Change: Implications for Landscape Design," in: *Managing and Designing Landscapes for Conservation: Moving from Perspectives to Principles,* D. B. Lindenmayer and R.J. Hobbs, Eds. Conservation Science and Practice Series 1, Oxford: Blackwell Publishing, 2007, pp. 349-366.

[5] C. Nilsson, R. Jansson, B. Malmquist, and R. J. Naiman, "Restoring Riverine Landscapes: The Challenge of Identifying Priorities, Reference States, and Techniques," *Ecology and Society,* vol. 12 (1), art. 16 (online), 2007.

[6] D. B. Lindenmayer and R. J. Hobbs, "Aquatic Ecosystems and Integrity," in: *Managing and Designing Landscapes for Conservation: Moving from Perspectives to Principles,* D. B. Lindenmayer and R.J. Hobbs, Eds. Conservation Science and Practice Series 1, Oxford: Blackwell Publishing, 2007, pp. 473-475.

[7] D. Newburn, S. Reed, P. Berck, and A. Merenlender, "Economics and land-use change in prioritizing private land conservation," *Conservation Biology, vol. 19, pp. 1411-1420, 2005.*

[8] J. A. Wiens, "Does Conservation need Landscape Ecology? A Perspective from both sides of the Divide," in: *Managing and Designing Landscapes for Conservation: Moving from Perspectives to Principles,* D. B. Lindenmayer and R.J. Hobbs, Eds. Conservation Science and Practice Series 1, Oxford: Blackwell Publishing, 2007, pp. 479-493.

[9] J. F. Franklin and M. E. Swanson, "Forest landscape Structure, Degradation and Condition: Some Commentary and Fundamental Principles," in: *Managing and Designing Landscapes for Conservation: Moving from Perspectives to Principles,* D. B. Lindenmayer and R.J. Hobbs, Eds. Conservation Science and Practice Series 1, Oxford: Blackwell Publishing, 2007, pp. 131-145.

[10] J. M. Scott and T. H. Tear, "What are we conserving? Establishing Multiscale Conservation Goals and Objectives in the Face of Global Threats," in: *Managing and Designing Landscapes for Conservation:*

Moving from Perspectives to Principles, D. B. Lindenmayer and R.J. Hobbs, Eds. Conservation Science and Practice Series 1, Oxford: Blackwell Publishing, 2007, pp. 494-510.

[11] RAMSAR Bureau, *The Ramsar Convention on Wetlands. Key Documents.* Available via http://www.ramsar.org/index_key_docs.htm.

[12] H. Joosten and D. Clarke, *Wise use of Mires and Peatlands.* International Mire Conservation Group & International Peat Society NHBS Ltd., Totnes, 2002.

[13] R. K. A. Morris, I. Alonso, R. G. Jefferson, and K. J. Kirby, "The creation of compensatory habitat – Can it secure sustainable development?" *Journal for Nature Conservation*, vol. 14, pp. 106–116, 2006.

[14] C. Schleupner, "Estimation of wetland conservation potentials for optimal land use allocations in Europe," *FNU-135*, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg, 2007.

[15] C. Schleupner and U. A. Schneider, "A cost-efficient spatial site-selection model for European wetland conservation," *FNU-159*, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg, 2008.

[16] U. A. Schneider, J. Balkovic, S. De Cara, O. Franklin, S. Fritz, P. Havlik, I. Huck, K. Jantke, A. M. I. Kallio, F. Kraxner, A. Moiseyev, M. Obersteiner, C. I. Ramos, C. Schleupner, E. Schmid, D. Schwab, and R. Skalsky, "The European Forest and Agricultural Sector Optimization Model – EUFASOM," *FNU-156*, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg, 2008.

[17] A. Ando, J. Camm, S. Polasky, and A. Solow, "Species distributions, land values, and efficient conservation," *Science*, vol. 279, pp. 2126-2128, 1998.

[18] S. Polasky, C. Costello, and A. Solow, "The economics of conserving biological diversity," in: *The Handbook of Environmental Economics*, vol. 3, J. Vincent and K. G. Maler, Eds. Amsterdam: Elsevier, 2005, pp. 1517-1560.

[19] R. Naidoo and W. L. Adamowicz, "Economic Benefits of biodiversity conservation exceed costs of conservation at an African rainforest reserve," *Proc. Natl. Acad. Sci. USA*, vol. 102, pp. 16712-16716, 2005.

[20] J. Gan and B. A. McCarl, "Measuring transnational leakage of forest conservation," *Ecological Economics*, vol. 64, pp. 423-432, 2007.

[21] A. Bruvoll and T. Fæhn, "Transboundary effects of environmental policy: Markets and emission leakages," *Ecological Economics*, vol. 59, pp. 499-510, 2006.

GIS-BASED ESTIMATION OF WETLAND CONSERVATION POTENTIALS IN EUROPE

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Abstract. In the EU different utilization demands compete with each other and space is limited. As a consequence, socio-economic considerations and economic activities play therefore an important part in land use management and conservation planning. Often the integration of conservation concerns in agricultural as well as forestry production land use models has been neglected. One reason is a lack of accurate and consistent basis data. Therefore, conservation studies that offer high-accuracy landscape information at the European level are often recommended by policy makers, but rarely realized. This study contributes to this problem by creating and preparing a wetland distribution model (SWEDI) for integration into the mathematical bottom-up land use assessment model EUFASOM, which studies synergies and tradeoffs between biodiversity conservation efforts, greenhouse gas mitigation options, as well as traditional agriculture and forestry. The basis of SWEDI is the optimal combination of existing spatial datasets to obtain the spatial distribution of wetlands by definition of flexible knowledge rules. The model distinguishes between existing wetlands and sites suitable for wetland restoration at 1 km resolution. It differentiates several wetland types and covers the whole EU-25 area. The results of the model may help to locate sites suitable for restoration programs, or for the introduction of faunistic corridors.

Keywords: *land use planning, restoration ecology, spatial analysis*

Introduction

Because of its settlement history, land utilization in Europe is diverse and complex. As a consequence, many natural ecosystems as wetlands are altered and experience degradation, fragmentation and loss. It is estimated that more than two thirds of all wetlands in Europe have been lost since beginning of the 20th century (LIFE 2007) because economically profitable land utilization requires drainage of the wetlands. Today, wetlands are considered to be among the world's most threatened ecosystems. Besides biotope reduction and habitat fragmentation wetland loss has been also made responsible for unprecedented flooding events and species declines (Dahl 2006). Because of natural habitat shortage latest conservation efforts include the option of restoration and creation of wetlands to meet the targets set out by the European Commission to halt biodiversity decline. But changing land use for food and, increasingly, biofuel production constitutes a great challenge to nature conservation. Conservationists are concerned that the promotion of bioenergy plantations in the context of climate change mitigation policies could threaten nature reserves and would lead to further biotope loss.

In the past the integration of conservation concerns in agricultural as well as forestry production land use models has often been neglected (Franklin and Swanson 2007). One reason is often a lack of accurate and consistent basis data. Therefore, conservation studies that offer high-accuracy landscape information at the European level are often recommended by policy makers, but rarely realized by researchers (Wascher 2000, Klijn 2002, Scott and Tear 2007, Wiens 2007).

Usually, economic land use models refer to country statistics as base data. These data differ in spatial accuracy, reliability, acquisition data and class definition. Aggregating statistical and spatial data from many sources into one database often causes low spatial accuracy and complicates comparability, especially between eastern and western European countries. So is the spatial distribution of wetlands in Europe not well known except for large wetland areas or for wetlands of special ecological interest (Merot et al. 2003). Even those wetland areas, which have been identified on the behalf of European Environment Agency (*EEA*), correspond to wetland areas of ecological interest and represent only a rather small part of all wetland areas (Bernard 1994). Some wetland studies modeled wetland distribution at global scales (Matthews and Fung 1987, Aselmann and Crutzen 1989, Stillwell-Soller et al. 1995, Joint Research Centre 2000, Lehner and Döll 2004). Due to its global perspective, the spatial resolution is coarse and wetlands are seldom differentiated in detail what makes the use of these data for conservation studies in European scale inappropriate. The most detailed consistent information about wetland habitats in Europe offers the EUNIS (European Nature Information System) Database with the distinction of over 2600 terrestrial habitat classes at the fourth level (Moss and Davies 2002 a,b). However, the corresponding EUNIS habitat type map (European Topic Centre on Biological Diversity (ed.)) that has been created using mainly aggregated CORINE data refers only to the first level (= 10 major habitats) of the EUNIS habitat classification. Also, the CORINE biotopes data (European Commission 1991, Moss and Wyatt 1994, Moss et al. 1996, EEA 2000a) that are based on reported NATURA2000 sites do not represent the existing wetlands completely and are only available in terms of spots on the map without area size statements. At present, the CORINE data (EEA 2000b) is the most detailed land cover database covering the European Union. One disadvantage is the heterogeneity of the classes determined by functional land use and not by land cover itself. The digital map of the potential natural vegetation of Europe (Bohn and Neuhäusel 2003) shows a detailed classification and potential distribution of wetland vegetation types across Europe. However, this distribution is irrespective of human influences and therefore only conditionally suitable because river regulation, peat extraction or urbanization on former wetland areas often lead to changed wetland restoration potentials. In all it becomes clear that there are no digital land cover or vegetation maps of the EU that show detailed wetland distribution.

This study contributes to this problem by compiling spatially consistent information on wetlands differentiated by wetland types and characteristics using GIS-based techniques. Not only existing wetland habitats should be documented but also potential wetland restoration sites by considering actual land use options. This way a new methodology on broad scale distribution modeling is developed. The study presented here is an attempt to extend the distribution modeling process to a broad continental scale by keeping the spatial accuracy as high as possible. This is important because European wetlands are often fragmented ecosystems of small extent. Many wetlands are smaller than one $1km^2$. But improvements in data quality and availability as well as

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simplifications in earth observation techniques make the more detailed studies feasible. As a result the narrow stripes of alluvial forests or small isolated bogs may be better represented in broad-scale analyses of wetlands. Besides the importance of regional case studies, decision makers of European land use policies demand spatial ecosystem information at holistic scales. The resulting wetland distribution model is finally aimed to be integrated into the mathematical bottom-up land use assessment model EUFASOM (European Forest and Agricultural Sector Optimization Model), which is used to study synergies and trade-offs between wetland conservation efforts, greenhouse gas mitigation options including carbon sinks and bioenergy, and agriculture and forestry of Europe (Schneider et al. 2008). Through EUFASOM, economic wetland potentials for optimal land use options are determined under certain policy scenarios.

Methods

Definition of wetlands

Often wetland terms and definitions are not standardized. The RAMSAR Convention (Article 1.1) defines wetlands as "areas of marsh, fen, peat land or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters". In wetlands water is present at or near the surface of the land also if only for varying periods of the year. Wetlands vary widely in soil, topography, climate, hydrology, water chemistry, vegetation, and other factors, also because of human disturbance (Pott and Remy 2000, Dierssen and Dierssen 2001, Blume et al. 2002). In this study we concentrate on the natural freshwater or inland wetlands whose types are further defined in *table 1*.

Table 1. *Used wetland terms and their definitions, based on Cowardin et al.(1979), Mitsch (1994), Sanderson (2001)*

Common Wetland Names	**Definition**
Peatland	generic term of any wetland that accumulates partially decayed plant matter.
a. Bog	peat-accumulating wetland that has no significant inflows or outflows. Water and nutrient input entirely through precipitation; characterized by acid water, low alkalinity, and low nutrients. Peat accumulation usually dominated by acidophilic mosses, particularly sphagnum.
b. Fen	peat-accumulating wetland that receives some drainage from surrounding mineral soil. Usually dominated by sedge, reed, shrub or forest (→ swamp forest). Surface runoff and/or ground water have neutral pH and moderate to high nutrients.
Wet grassland (Marsh)	in European terminology a marsh has a mineral soil substrate and does not accumulate peat. Permanently or periodically inundated site characterized by nutrient-rich water and emergent herbaceous vegetation (grasses, sedges, reed) adapted to saturated soil conditions.
Wet forest	any wetland that is dominated by forest.
a. Swamp forest	wetland dominated by trees, most often forested fen. Depends on nutrient-rich ground water derived from mineral soils.
b. Alluvial forest	Periodically inundated forest areas next to river courses.

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The definition of inland wetlands also includes marshes and wet meadows dominated by herbaceous plants that are most often human made as well as shrub- or tree-dominated swamps. In Europe, inland wetlands are most common on floodplains along rivers and streams, along the margins of lakes and ponds, and in other low-lying areas where the groundwater intercepts the soil surface or where precipitation sufficiently saturates the soil (vernal pools and bogs). Many of these wetlands are seasonal and may be wet only periodically. The freshwater wetlands denote the most relevant areas for land use options implemented in EUFASOM. Open waters are considered separately.

Locating wetland potentials

The spatial wetland distribution model "Swedi" is developed as extraction tool to denote wetland allocations in Europe. In this respect GIS and spatial modeling are used as instrument to locate existing wetland areas as well as to identify the most suitable areas for wetland regeneration measures. This GIS model aims to depict the distribution of wetland areas at regional level and also at coarse geographic scale. This involves the integration of a variety of GIS datasets and multiple iterations of expert review and interpretation to delineate the potential wetland areas of Europe. We used the GIS tool ArcGIS9 for analysis.

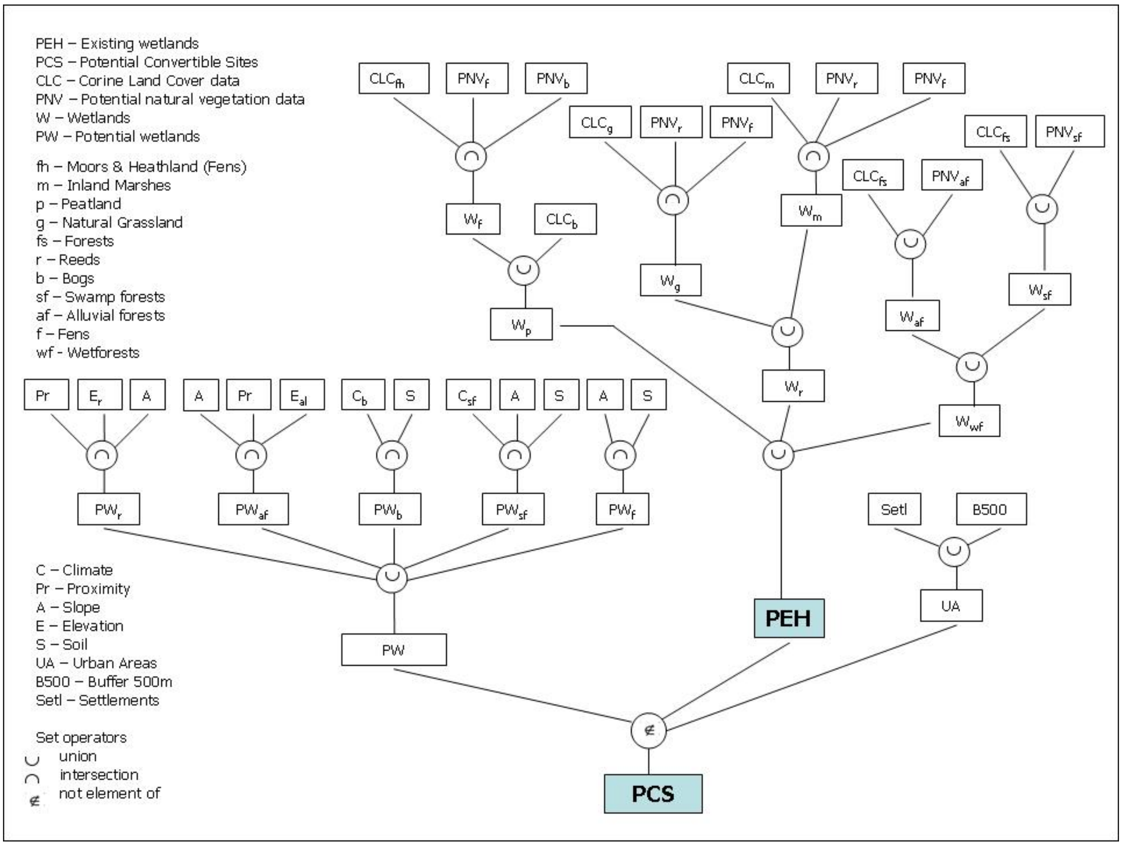

Figure 1. *The spatial wetland distribution model "Swedi"*

Figure 1 gives an overview of the Swedi (*Spatial wetland distribution*) model structure and its core input data. It is described in more detail in the following methodological section that is subdivided into two parts. The first deals with the evaluation of existing wetlands in Europe, and the second with the modeling of potential convertible sites for wetland restoration management.

Existing wetland habitats (PEH)

Existing wetland biotopes are defined as areas where wetlands with state close to nature actually appear within Europe. The analysis is executed with Model Builder and the Spatial Analyst Extension of ArcGIS9. The Corine land cover map 2000 with spatial resolution of 100 m serves as core base map (EEA 2000b). From the CORINE data, the following land cover classes have been extracted: moors & heathland (3.2.2.), inland marshes (4.1.1.), peat bogs (4.1.2.), inland waters and estuaries (5.1. and 5.2.2.), natural grassland (3.2.1.) and forests (3.1.). The EEA (1995) gives detailed definitions of each class. Within the spatial model the land cover class "peat bogs" serves as the only one that does not need to be altered to show existing "bog" wetlands, whereas all other selected land cover classes have to be split up separately: out of the generalized forest classes, only the wet forests, namely alluvial forests next to river courses and fen or swamp forests, are extracted through rule based statements using set operators. The CORINE classes "natural grassland" as well as "inland marshes" serve as base data for the model parameter "natural wet grasslands". In addition, moors, wet heaths and riverine and fen scrubs are extracted from the general class "moors and heathland". The map of the potential natural vegetation (PNV) of Europe (Bohn and Neuhäusel 2003) has been selected as source to locate the wetland sites within these CORINE land cover classes. The PNV map in general distinguishes following wetland types: a. tall reed vegetation and tall sedge swamps, aquatic vegetation (PNV class R), b. mires (S), c. swamp and fen forests (T), d. vegetation of flood plains, estuaries and fresh-water polders and other moist or wet sites (U). These types can then be further subdivided. We extracted these wetland types and intersected them with the corresponding CORINE data. Only those sites matching both attributes were considered as present existing wetland site. The remaining sites were assumed to be non-wetland. However, this does not exclude the probability of the non-wetland areas to be potential wetland restoration sites as is explained in more detail below. *Figure 2* gives examples of the intersection and extraction procedure.

In order to verify the accuracy of the distribution of existing wetlands in Swedi, resulting outputs must be compared with an independent data set (Verbyla and Litaitis 1989, Araujo et al. 2005). A description of general CORINE Land Cover data accuracy is found in the EEA Technical Report 7 (2006). In this study we use the CORINE biotopes database and parts of the RAMSAR list of wetlands of international importance (2008) for comparative analyses. The Corine biotopes (Version 2000) database is an inventory of major nature sites. The aim of the database was to enhance reliable and accessible information about vulnerable ecosystems, habitats and species of importance as background information for community environmental assessment. The wetland sites of the database are - among others - attributed with the size of the wetland. Site coordinates are included for easy localization of the biotopes within a GIS. We selected 50 freshwater wetlands from the database and compared their occurrence in the Swedi model considering spatial accuracy and wetland size. The same procedure has been applied to 50 selected RAMSAR sites. Additionally, the spatial extends of denoted NATURA2000 wetland sites as well as available biotope maps of individual sites are compared to the existing wetlands of Swedi.

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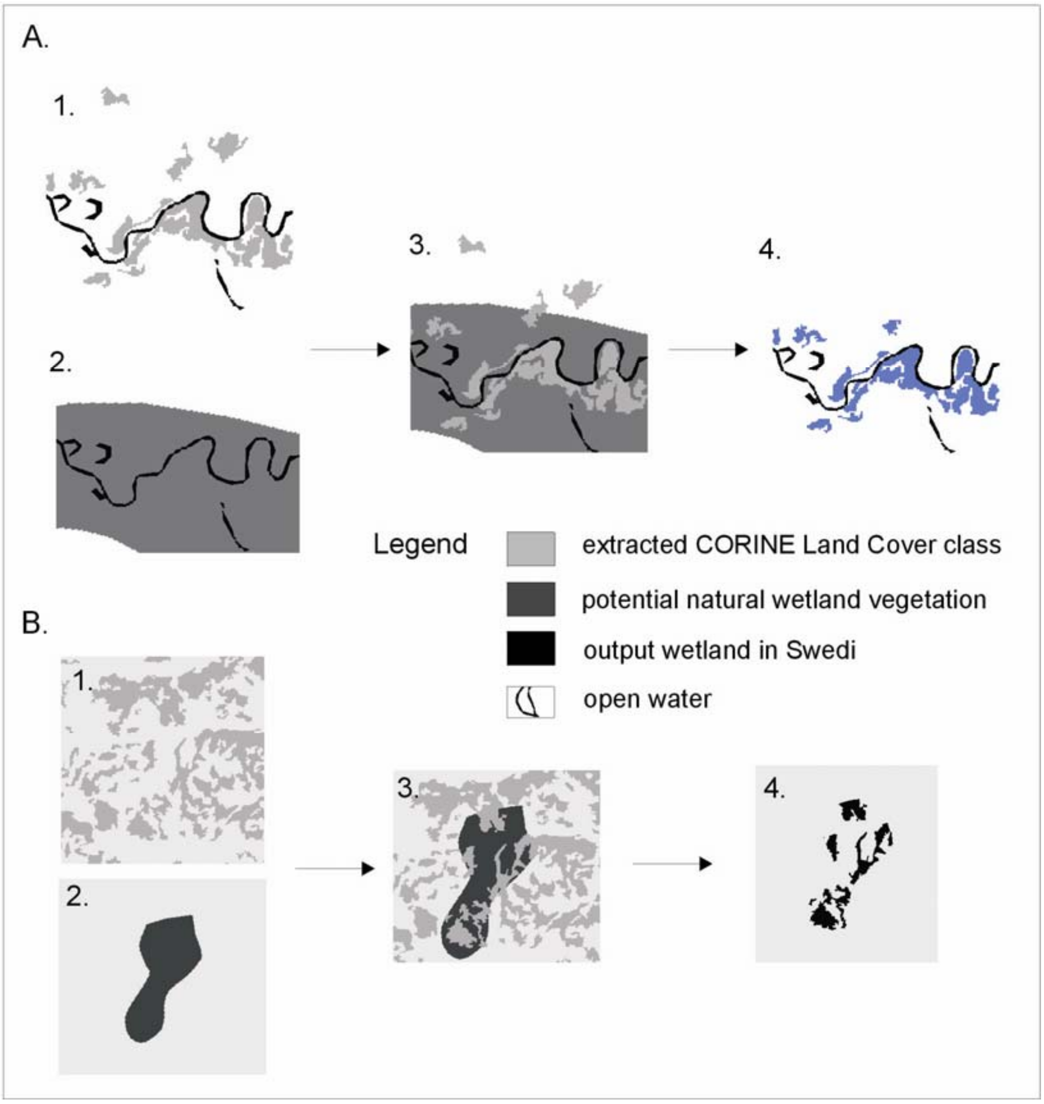

Figure 2. *two regional examples showing the methodology of the extraction procedure A. for wetforests by intersection of extracted CORINE Land cover class "broad-leafed forest" with extracted "swamp and fen forests" (PNV class T) and "vegetation of flood plains, estuaries and fresh-water polders and other moist or wet sites" (U) classes of the potential natural vegetation map of Europe. Shown is a section of the Elbe river between Dessau and Wittenberg / Germany. B. for moors, wet heaths and riverine and fen scrubs by intersection of extracted CORINE Land cover class "moors and heathland" with extracted "tall reed vegetation and tall sedge swamps, aquatic vegetation" (R) and "mires" (S) classes of the potential natural vegetation map of Europe. Shown is a region in the Grampian Mountains / Scotland.*

Potential convertible sites (PCS)

The second part of the GIS assessment evaluates potential convertible wetland sites. These areas may be used for location of restoration programs or habitat creational measures. The distribution of wetlands is explained by many dependent and explanatory variables. Important factors are the climatic, hydrological, geological, ecological and socio-economic conditions of the area. The classification of wetland distribution is therefore preferably based on analysis of these independent variables (Guisan and

Zimmermann 2000). The connection between the respective information of the database and the probable appearance of the wetlands is determined by assuming that there is a relationship between environmental gradients such as soil, climate, or slope and wetland distribution (Franklin 1995). We use traditional statistical methods based on observed correlation as well as geographically weighted regression analysis to analyze environment-wetland relationships. This proved to be useful concerning European scale analyses, because it allows for regional differences in relationships by estimating regression parameters that vary across space (Miller et al. 2007). Characteristic soil parameters, climate conditions, slope angles, and elevations are worked out for every wetland type on the basis of several literature resources (Brinson 1993, Kuntze et al. 1994, Ellenberg 1996, Succow and Joosten 2001, BfN 2004). Through this, rule-based statements are derived about the potential appearance of the target wetland types. In combination with geographical data these statements allow the identification and localization of potential wetland sites within a GIS. *Table 2* illustrates the resulting factors that characterize each wetland type.

Table 2. *Rating factors that characterize each wetland type (after Brinson 1993, Kuntze et al. 1994, Ellenberg 1996, Succow and Joosten 2001, BfN 2004)*

	Soil	Slope Angle	Climate	Proximity to open waters	Elevation
Fen	X	X			
Bog	X		X		
Swamp Forest	X	X	X		
Alluvial Forest		X		X	X
Reeds		X		X	X

Former wetland areas are considered as most suitable for wetland recreation (Ellenberg et al. 1991, Wheeler et al. 1995, Schultlink and Van Vliet 1997). These might be arable fields, pasture lands, fallow or forested areas on sites of former wetlands that have been intensely changed. Actual soil conditions might give hints for potential wetland biotopes. We use the European soil database (Joint Research Centre 2004) of 1 km grid resolution and extract following potential wet- and peatsoil-classes: gleysols, fluvisols, gleyic luvisols, histosols, gleyic podzol. The wetland types bogs, swamp forests and fens are considered to be soil dependent (cf. *table 2*).

The climate parameter is only applied for the parameters bogs and swamp forests; all other wetland types are rated as azonal and therefore relatively climate independent (Succow and Jeschke 1990, Ellenberg 1996, Walter and Breckle 1999). The climate variables of the wetland types shown in *table 3* are extracted from the explanatory text of the map of the Natural Vegetation of Europe (BfN 2004) and are mainly based on Walter and Lieth (1967). We use the attributes temperature (max temp of warmest month, min temp of coldest month, average annual) and precipitation (average annual) of the Bioclim and Worldclim data at spatial grid resolution of 30 arc-seconds (~ 1 km²).

Table 3. *Wetland type characteristics concerning their climate ranges of occurrence (after BfN 2004, Walter and Lieth 1967)*

Wetland type	Average annual temperature (in °C)	Average precipitation (mm/year)	Max temp av. warmest month (°C)	Min temp av. coldest month (°C)
Bogs	3 - 6	300 – 1 000	12 - 17	-15 – (-2)
	9 - 11	1 200 – 2 000	13 - 15	5 – 7
	3 - 8	1 400 – 2 400	10 - 12	-2 - 0
	5 – 9,5	550 – 1 500	14 - 19	-3 - 5
	4 – 5,5	900 – 1 400	11 - 12	-3 – 0
	3.5 – 7.8	530 - 630	17.5 - 19	-10 – (-2)
	- 10 - 1	200 - 500	8 - 13	-25 – (-10)
Aapa mires (fens)	- 3 - 5	250 - 700	8 - 15	-17 – (-5)
transitional mires (fens)	0 - 5	500 - 870	8 - 14	-12 – (-3)
degraded bogs, now wet forests	8 - 9	600 – 1 200	15 - 16	0 – 4
wet forests	6 - 11	450 – 1 000	16 - 21	-5 – 0
	14 - 15	> 1 000	20 - 22	6 – 8
	9 - 10	550 – 1 000	15 - 16	4 - 5

The analyses of elevation dependent wetland types might also refer to climate or relief conditions (Merot et al. 2003). However, we are confined to the statements of highest occurrences of respective wetland types by the explanatory text of the PNV map of Europe (BfN 2004). The base elevation data for Europe are taken from GTOPO30 data a global digital elevation model at spatial resolution of 30 arc-seconds (sheets: W020N90, E020N90, W020N40, E020N40) (USGS 1996). In addition to that the bio-geographical regions map of Europe (EEA 2002) contribute to the elevation parameter by dividing the height variables into several bioclimatic regions that better reflect the height-limits than country based distinctions of regions. *Table 4* shows the wetland type characteristics concerning their maximum elevation occurrence range.

Table 4. *Wetland type characteristics concerning their maximum elevation occurrence range (after Brinson 1993, Kuntze et al. 1994, Ellenberg 1996, Succow and Joosten 2001, BfN 2004)*

Wetland type	Biogeographical Region	Elevation (m)
Reeds	Boreal, alpine (scand.)	<= 500
Reeds	Alpine (other), all others	<= 800
Alluvial forests	Boreal, alpine (scand.)	<= 500
Alluvial forests	Alpine (other), all others	<= 1 200

The map of bio-geographical regions is based on the PNV map (Bohn and Neuhäusel 2003). It distinguishes between six bio-geographical regions in the EU-25, namely Alpine, Boreal, Continental, Atlantic, Mediterranean, and Pannonian. Alluvial forests and reeds are considered elevation dependent, less because of climatic conditions, but more due to loss of suitable ground conditions (Ellenberg 1996, Mulamoottil et al. 1996, BfN 2004). The climate dependent wetlands are assumed to limit their height occurrence by this parameter itself. An elevation constraint is therefore not necessary.

Only the fens are assumed neither climate nor elevation dependent. They solely refer to soil conditions and the slope parameter.

The slope parameter is evaluated based on the elevation data using the Spatial Analyst extension of Arc GIS9. Only those areas with a slope angle below 1° are assumed suitable for the wetland types reeds, alluvial forests, swamp forests and fens (Mulamoottil et al. 1996, Lyon 2001). Due to scale reasons the slope angle is set to this maximum extension and does not distinguish slope angles below that point as has been done in case studies of larger scale (Tsihrintzis et al. 1998, Helmschrot and Flügel 2002).

Also the proximity to inland waters or to existing inland peatland is an important criterion for localization of target areas if other parameters are fulfilled. The proximity criterion has been initially set to 500 meters. But this border may be handled flexible. For implementation in the GIS-based model we establish multiple ring buffers around inland waters and other bog areas with radius of the defined proximity. The extension of potential water surrounding wetland sites like alluvial forests can be detected by a combination of the proximity with other parameters.

Highly populated areas as are towns and cities provide very limited space for wetland restoration or construction. For this reason, potential convertible sites are only modeled for agriculturally used areas, grasslands and forests by using pseudo-absences for urban areas (cf. Chefaoui and Lobo 2008). Urban areas including a buffer zone of 800 meters are omitted by the model. We use the Corine Land Cover 2000 data for determination of these sites.

For accuracy assessment the potential wetland sites are correlated with the spatial distribution of the existing wetlands. And in a last step, the existing wetland sites are subtracted from the preliminary results to obtain only data on potential convertible areas. All data encompass the whole EU-25 states boundaries with exception of Malta and Cyprus that are not included in the analysis.

Results

The comparison of existing wetlands with samples of the independent data sets (RAMSAR wetlands and CORINE biotopes) shows that all selected wetlands of the databases are also represented in Swedi. The differences lie in the area extent of the respective wetlands: In over 70% of the cases the model overestimates the size of an existing wetland. One reason is the fact that the existing wetlands module of the Swedi model accepts uncertainties about the state of the wetland ecosystem also due to scale reasons. We are not able to distinguish between afforestations or natural alluvial forests in a floodplain, for example, what also might lead to overestimation errors of the results. 26% of the sites are underestimated in size. The difficulty is the accurate demarcation of wetlands and its types from open waters and terrestrial land due to their dynamic characteristics and their fluctuating and undefined borders. Often open waters are integrated into the wetland definitions of the databases whereas these wetland types are considered separately in the Swedi model. However, more than 85% of the selected wetlands stay within the defined uncertainty range of 15% deviation. No significant differences in accuracy are found between northern and southern or eastern and western European wetlands. *Figure 3* exemplarily shows a comparison of available spatial wetland data of Natura2000 with Swedi data as used for the accuracy assessment. Not all wetlands are implemented in the Natura2000 network and therefore it is reasonable

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that some existing wetlands of Swedi are not represented in the Natura2000 data. Also the spatial extend of the wetlands differ due to the fact that the wetland dimensions are difficult to define and that often the Natura2000 data include other biotopes combined in biotope complexes or buffer zones as well. However despite its inconsistencies in extent, more than 91 % of the Natura 2000 wetlands data are also represented in Swedi.

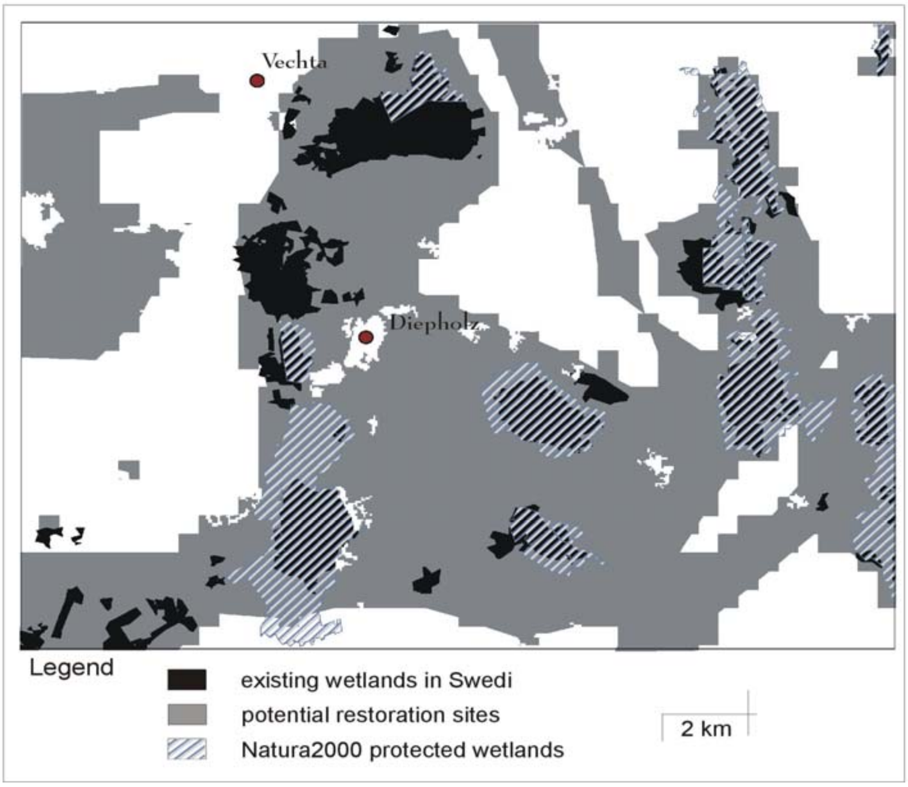

Figure 3. *Example of the accuracy assessment in the case of the Dümmer Region in Lower Saxony / Germany. We used spatial information of wetlands implemented in the Natura2000 sites and correlated them to the wetland distribution of Swedi.*

Other comparisons with individual biotope maps on regional scale revealed more uncertainties and weaknesses of Swedi. This is due to the fact that wetlands below a certain extent are not well represented in Swedi and therefore some present wetlands may be underestimated or indicated as restoration site. At the same time the restoration sites overestimate the extent of potential wetland sites because of coarse base data in elevation or soil, for example, that do not respect geographic diversity at landscape scale. Under consideration of these limitations Swedi is only useful for general European scale studies.

Problems in comparability arose by drawing comparisons with a simple per-country aggregation of Swedi wetland areas to results of the Pan European Wetland Inventory (PEWI) (Nivet & Frazier 2004). This may simply be due to the fact that both datasets apply to different wetland type determinations and basis data. Whereas the Swedi data are spatially explicit and rely on other spatial and geophysical data, the PEWI data are on country scale and rely on different kinds of national wetland inventories or statistics. For this reason an accuracy assessment with PEWI data has been refused.

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The outcomes of Swedi are spatially explicit data on wetland distribution in Europe. The results may be illustrated through wetland distribution maps. *Figure 4* shows the spatial distribution of existing habitats (dark grey) and potential convertible sites (light grey) exemplarily for selected areas. The whole illustrated data set is available for download at http://www.fnu.zmaw.de/Dipl-Geogr-Christine-Schleupner.5728.0.html.

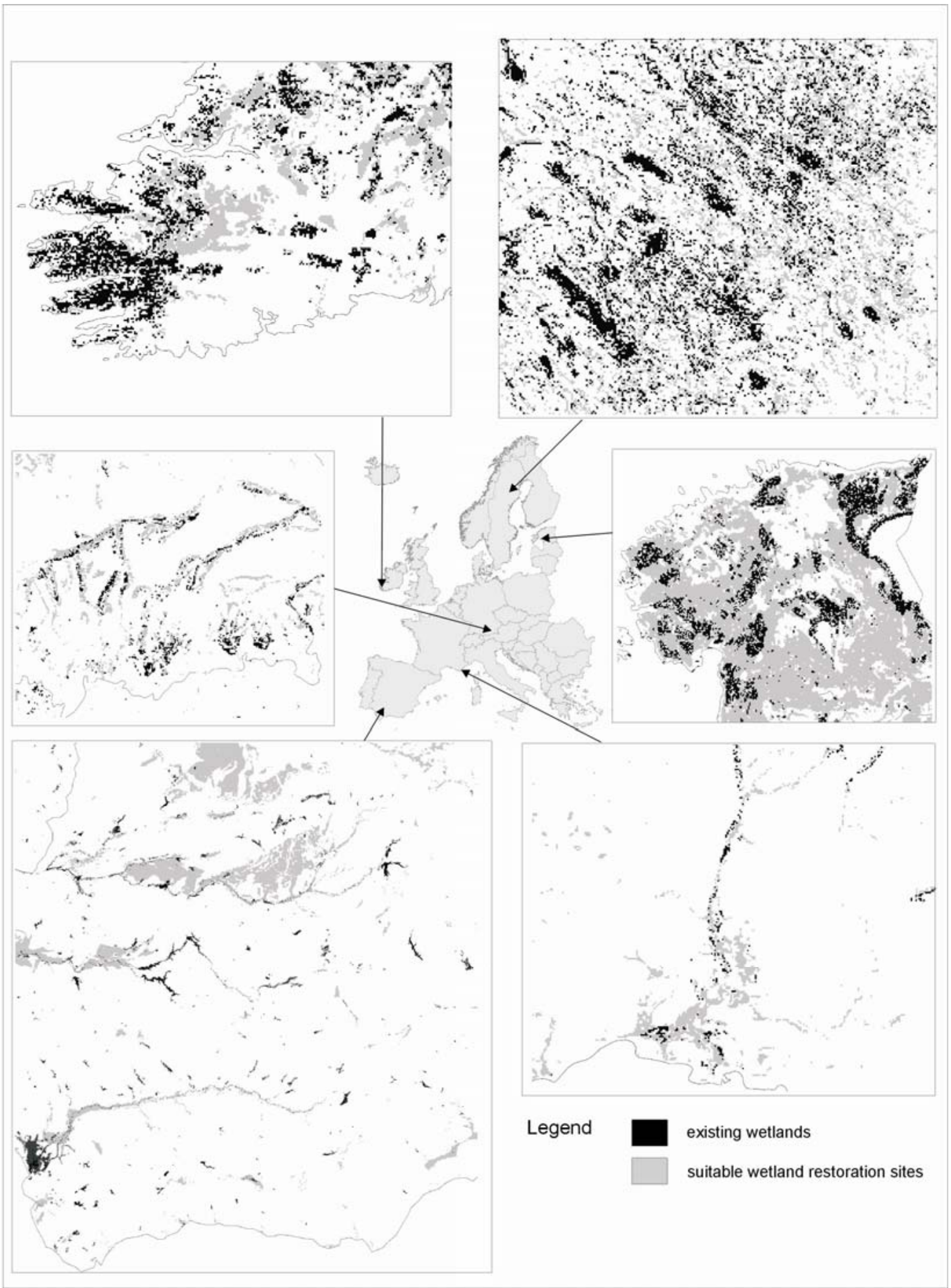

Figure 4. *Detailed examples of the spatial distribution of potential existing habitats (dark grey) and potential convertible sites (light grey) of Swedi.*

An analysis of the Swedi map reveals that the majority of existing wetland areas (PEH) is situated in the northern and western European countries, while the potential convertible sites (PCS) are well distributed over the EU. In total, about 4% of the EU-25 land area consists of potentially existing wetlands and an additional 21% of the land areas are potential convertible to wetland sites. This constitutes a maximum share of wetlands of one fourth of the total land area of the EU-25. *Figure 5* gives an general overview of the total area (in 1 000 ha) of existing and the potential convertible wetland sites per country derived from Swedi.

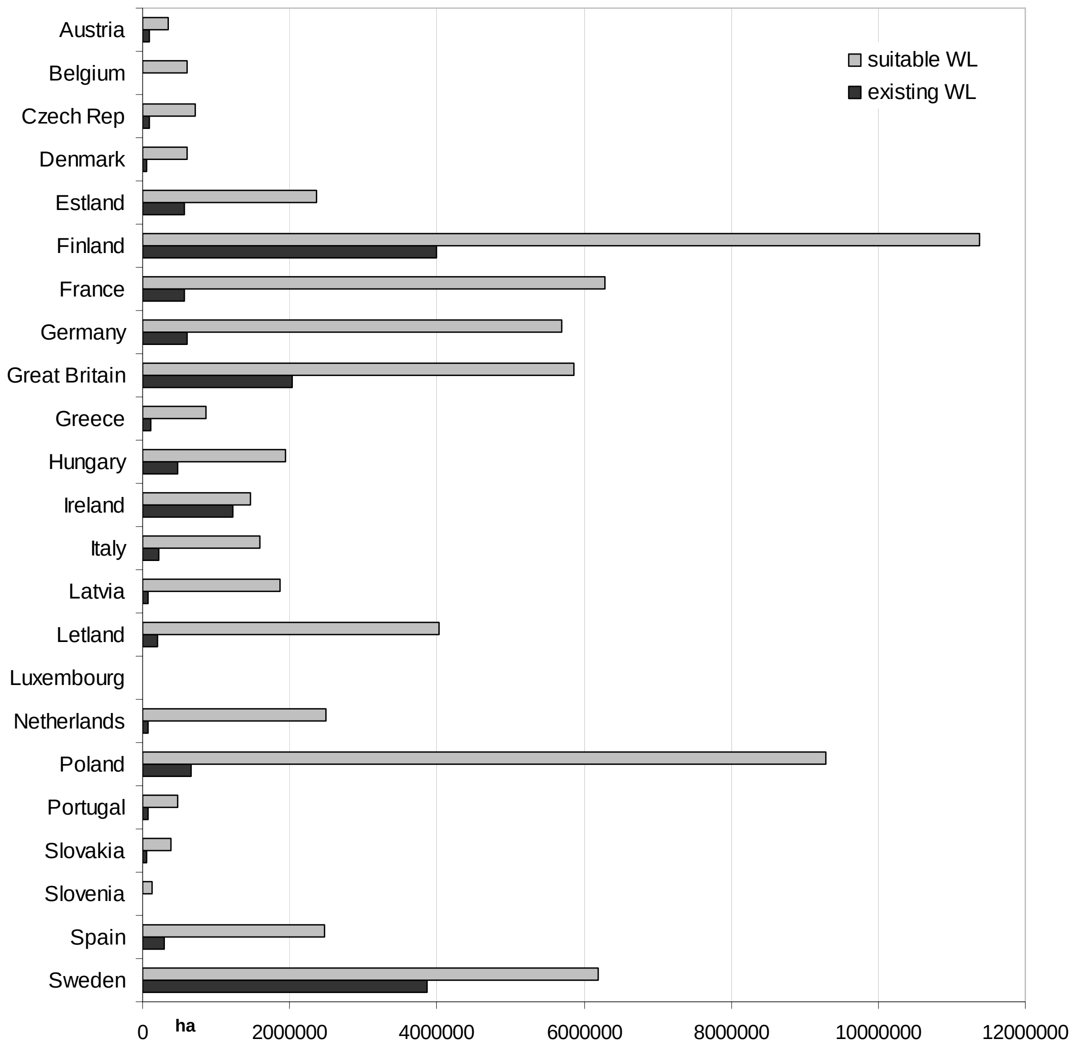

Figure 5. *total wetland area (in 1000 ha) per country distinguished after existing wetlands and suitable restoration sites*

Even if not only restricted to formerly existing wetland areas the extent of potential wetland sites also give an impression of wetland loss. Open waters are excluded from the evaluation. Finland and Sweden own by far the most extending existing wetland areas with about 3.8 million ha wetlands. Also Ireland has great amounts of existing wetland areas (about 1.3 million hectares) but less in comparison to the Scandinavian countries. Finland and Sweden also lead in the amount of potential convertible wetland sites. In this category Poland, Great Britain as well as France and to a certain extent Germany as well show high amounts of land suitable for wetland restoration.

The relationship between wetland areas and country size (see *Figure 6*) displays a different picture: Now Ireland shows the highest wetland rate (PEH) with about 19% of its country area, followed by Estonia (13%) and Finland (12%). Also Sweden and the UK with 8.7% and 9.25% of their country size own a high existing wetland rates in comparison to other countries whose amounts lie between 0.03% (Luxembourg), 0.6% (Spain), and 5.1% (Hungary), or 3.2% PEH of the country area in the case of Latvia, for example.

Concerning the PCS per country area, Latvia (68%), the Netherlands (75.6%), and Estonia (66%) have the highest relative potentials. The PCS rate of Finland, Poland, Great Britain, and Ireland amounts to between 31 and 49% per country area. In this case Denmark, Sweden and Germany have potentials of about 16 to 20% and the PCS rate of all other countries amount between 5.1% as lowest rate in Austria and 12.5% in France.

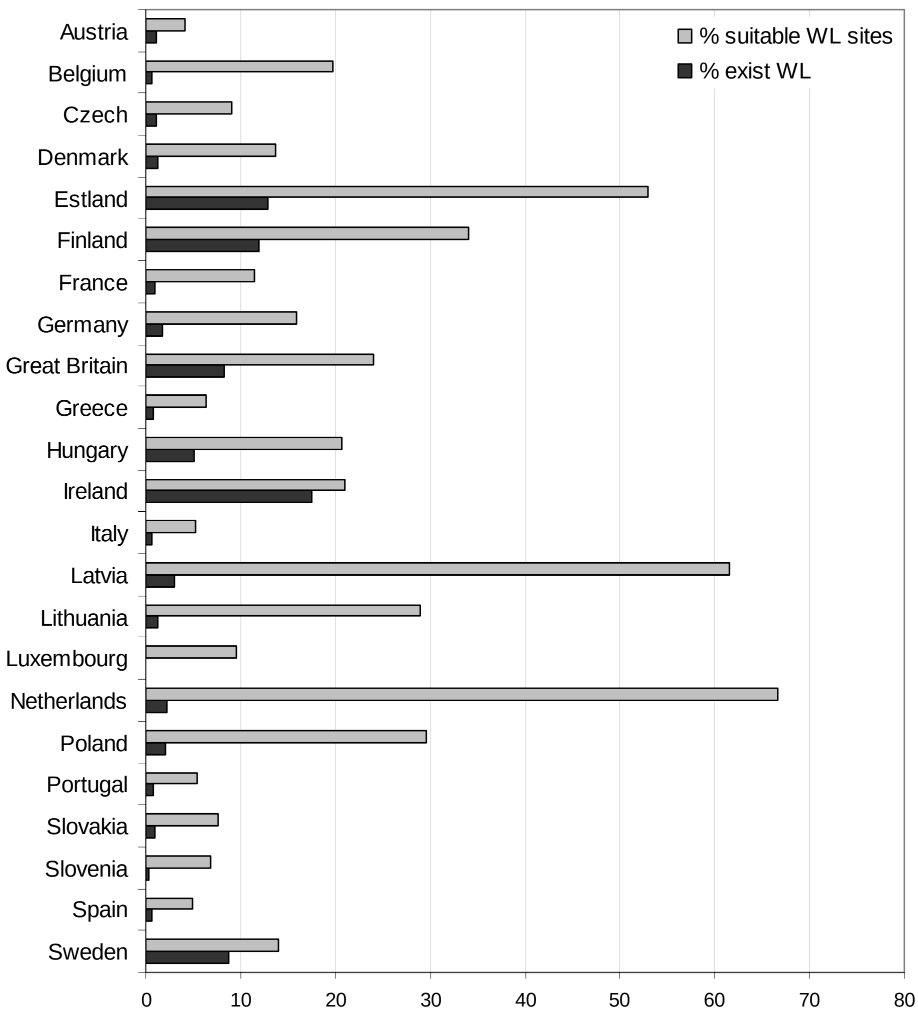

Figure 6. *Relative wetland area (%) per country*

Through Swedi the main wetland types peatland (fen/bog), wet forests (alluvial forest/ swamp forest) and wet grassland and its spatial potentials are visualized. Its results make evident that the potential wetland restoration sites are often overlapping. This is especially true for peatlands. Moreover, some wetland types might be temporarily successional vegetation states of others within the wetland biotope complexes. Main areas of existing peatland are the Scandinavian countries and Ireland. Here, as well as in Scotland, Eastern Poland and Estland also highest amounts of potential bog areas are found. All other illustrated potential peatland areas may be favorable for fen restoration. Fens can also be created on potential bog areas, but this constraint does not work vice versa. It is remarkable that the formerly extending bog areas of North-Western Germany, that have been mainly drained and exploited during the last centuries, show fen instead of expected bog potentials in Swedi. This might be due to model uncertainties or errors, but can as well be a hint that the bogs have developed under different climatic conditions from the end of the last ice age and are relicts only. The destruction of these bog areas possibly means an unrecoverable demise of the ecosystem. Like wet grasslands also wet forests are found along water courses and in the proximity of other open waters. Especially the swamp forests are constricted to wet soils and to specific climate conditions. Main areas of potential swamp forest sites are therefore found in Central and Eastern Europe but also in the UK. In northern and western European countries the wet forested area does not exceed the peatland areas whereas in Germany and Poland and further south wet forests are the most extending wetland types. Extending areas of potential wet grassland sites are shown in Scandinavia, Estland, and Ireland, but also in Hungary. Wetland areas need to have at least a size of one hectare to be included into the spatial model. Therefore, often reeds along lakeshores are not shown in the results and Finland even counts no wet grasslands even though there are reeds growing along many waters.

Summarizing the total PCS areas distinguished after the main wetland types for the European countries one gets following results: a maximum area of respectively 1 329 200 km², 643 300 km² and 305 700 km² could be potentially used for additional bog, additional fen as well as additional wet forest creation. It must be noted that these data are no absolute numbers, but moreover provide an informative basis of potential wetland restoration area.

Discussion

There is a growing demand of policy makers and researchers for high-accuracy landscape information at the European level. Despite numerous data on land use in Europe, a detailed analysis of the distribution of wetlands and potential restoration sites has been lacking so far. We developed a detailed wetland distribution map in European scale with high spatial resolution. Not only does it distinguish between different wetland types but also between existing and potential convertible wetland restoration sites; information that has not been available before. Whereas the evaluation of existing wetlands relies on a cross-compilation of existing spatial datasets, the potential wetland restoration sites are determined by definition of flexible knowledge rules in combination with geographical data. The orientation towards physical parameters and the allowance of overlapping wetland types characterizes the Swedi model. The detailed spatially explicit wetland classification of Swedi allows connections to other habitat databases, for example EUNIS, as well.

The accuracy of Swedi is strongly restricted by the availability and quality of geographical data. For example, the soil information is generally poor and often misleading from the standpoint of wetland functionality. The same holds for the elevation and slope data. Also the water factor is only indirectly integrated into the model through climate and soil data. As long as these detailed Pan-European data are unavailable provides Swedi a static estimation of wetland potentials suitable for broad scale studies that may be analyzed at landscape scale in more detail. The utilization of GIS makes the methodology highly applicable and easily to improve concerning data sources.

The accuracy assessment showed uncertainties in the wetland size and extent that can be explained through base data uncertainties but also through differences in wetland definition and its assignment. Varying analogies in accuracy of different wetland types is more a reason of scarce and inhomogeneous reference data and less of dissimilar modeling precision. Due to the fact that with Swedi only those wetlands with an area extent of more than 1 ha are displayed, the total wetland distribution may be underestimated. Many wetlands, especially those in central and southern Europe, are very small-sized and its implementation in broad scale maps is still not realized. However, we found no differences in accuracy between northern and southern wetlands. Another uncertainty is the state of the ecosystem of the existing wetlands. In Swedi we are not able to make statements about the naturalness of the site. Nevertheless, the comparison of Swedi with independent datasets of wetland biotopes proved high accuracy of the existing wetland sites in the Swedi model and the area extent is mainly reproduced within the uncertainty range.

The direct use of country aggregated Swedi data by simple polygon measurement as shown in the results section should be regarded with caution. The data give useful results but the European scale should be used with care for area estimation because it can give strongly biased results. In principle, the direct use of such data for estimation is only acceptable when no other data are available (Gallego & Bamps 2008). And for the spatially explicit estimation of wetland distribution no other homogeneous data exist in Europe.

The knowledge of the extent and distribution of wetlands is important for a variety of applications. This study applies an empirical distribution model to wetland ecosystems in European scale. These data can be used as ground information for further studies, for example helping to locate sites suitable for renaturation programs, or for the introduction of faunistic corridors respecting the Natura 2000 network of sites. The application of the model in nature conservation issues favours the success in regional conservation planning. The Swedi model on the other hand is meant to be integrated into the economic optimization EUFASOM model to evaluate the economic wetland potentials per EU-country (Schneider et al. 2008). The promotion of bioenergy plantations in the context of climate change mitigation policies constitutes a great challenge to nature conservation, because land use changes could threaten the availability of land for nature reserves and would lead to further biotope loss. By integrating the spatially explicit biotope information of Swedi into the economic land use model EUFASOM, the costs and potentials of different land utilizations as well as optimal conservation opportunities are evaluated.

Furthermore, so far Swedi builds the base data for European biodiversity studies of endangered wetland species that are analyzed for systematic conservation planning options. It is of utmost importance to provide accurate base data for the management and planning of conservation areas. This study offers some first guidelines but is also intended for an impulse of discussion on improvements of such data. The next enhancing step of Swedi besides base data refinements is to make this static extraction tool dynamic through the integration of hydrologic parameters for questions concerning climate change, conservation and land use planning options.

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REFERENCES

[1] Araújo, M.B., Pearson, R.G., Thuiller, W., Erhard, M. (2005): Validation of species-climate impact models under climate change. – Global Change Biology 11: 1504-1513.

[2] Aselmann, I., Crutzen, P.J. (1989): Global distribution of natural freshwater wetlands and rice paddies, their net primary productivity, seasonality and possible methane emissions. – Journal of Atmospheric Chemistry 8 (4): 307-358.

[3] Bernard, P. (1994) : Les zones humides; rapport d'évaluation. Comité interministériel de l'évaluation des politiques publiques. Commissariat au Plan. – La Documentation Francaise, Paris.

[4] BfN (ed.) (2004): Explanatory Text to the Map of the Natural Vegetation of Europe. – Landwirtschaftsverlag, Münster.

[5] Blume, H.-P., Brümmer, G.W., Schwertmann, U., Horn, R., Kögel-Knaber, I., Stahr, K., Auerswald, K., Beyer, L., Hartmann, A., Litz, L., Scheinost, A., Stanjek, H., Welp, G., Wilke, B.-M. (2002): Scheffer / Schachtschabel. Lehrbuch der Bodenkunde, 15th edition. – Ferdinand Enke Verlag, Stuttgart.

[6] Bohn, U., Neuhäusel, R., with contributions by Gollub, G., Hettwer, C., Neuhäuslová, Z., Raus, T., Schlüter, H., Weber, H. (2003): Karte der natürlichen Vegetation Europas / Map of the Natural Vegetation of Europe. Scale 1 : 2 500 000. – Landwirtschaftsverlag, Münster.

[7] Brinson, M.M. (1993): Hydrogeomorphic Classification for Wetlands. – US Army Corps of Engieneers, Wetland Research Program. TR: WRP-DE-4, Washington DC.

[8] Chefaoui, R.M., Lobo, J.M. (2008): Assessing the effects of pseudo-absences on predictive distribution model performance. – Ecological Modelling 210: 478-486.

[9] Cowardin, L.M., Carter, V., Golet, F.C., LaRoe, E.T. (1979): Classification of wetlands and deepwater habitats of the United States. – US Fish & Wildlife Service, Washington DC.

[10] Dahl, T.E. (2006): Status and trends of wetlands in the conterminous United States 1998 to 2004. – US Department of the Interior, Fish and Wildlife Service, Washington DC.

[11] Dierssen, K., Dierssen, B. (2001): Ökosysteme Mitteleuropas „Moore". – Ulmer, Stuttgart.

[12] EEA (ed.). (1995): CORINE Land Cover. Part 2: Nomenclature. – Available via http://reports.eea.europa.eu/CORO_landcover/en.

[13] EEA (ed.). (2000 a): CORINE Biotopes Database. – Available via http://dataservice.eea.eu.int/dataservice.

[14] EEA (ed.). (2000 b): CORINE Land Cover 2000 Database, 100 m. – Available via http://dataservice.eea.eu.int/dataservice.

[15] EEA (ed.). (2002): The Biogeographical Regions Map of Europe. – European Environment Agency, Copenhagen. Available via http://dataservice.eea.eu.int/dataservice.

[16] EEA (ed.). (2006): The thematic accuracy of Corine Land Cover 2000. Assessment using LUCAS (land use/cover area frame statistical survey). – European Environment Agency, Copenhagen.
[17] Ellenberg H., Arndt, U., Bretthauer, R., Ruthsatz, B., Steubing, L. (1991): Biological Monitoring – Signals from the environment. – GATE publication Vieweg, Braunschweig.
[18] Ellenberg, H. (1996): Vegetation Mitteleuropas mit den Alpen, 5th edition. – Ulmer, Stuttgart.
[19] European Commission (1991): CORINE biotopes. The design, compilation and use of inventory of sites of major importance for nature conservation in the European Community. – EUR 13231 EN. Brussels.
[20] European Topic Centre on Biological Diversity (ed.) (1993–2006): Introduction to EUNIS database. – Available via http://eunis.eea.europa.eu/.
[21] Franklin, J. (1995): Predictive vegetation mapping: geographic modelling of biospatial patterns in relation to environmental gradients. – Prog. Phys. Geogr. 19: 474-499.
[22] Franklin, J.F., Swanson, M.E. (2007): Forest Landscape Structure, Degradation and Condition: Some Commentary and Fundamental Principles. pp. 131-145. – In: Lindenmayer, D.B., Hobbs, R.J. (eds.) Managing and Designing Landscapes for Conservation: Moving from Perspectives to Principles. Conservation Science and Practice Series 1, Blackwell Publishing, Oxford.
[23] Gallego, J., Bamps, C. (2008): Using CORINE land cover and the point survey LUCAS for area estimation. – International Journal of Applied Earth Observation and Geoinformation 10 (4): 467-475.
[24] Guisan, A. and N. E. Zimmermann. 2000. Predictive habitat distribution models in ecology. – Ecological Modelling 135: 147-186.
[25] Helmschrot, J., Flügel, W.-A. (2002): Land use characterization and change detection analysis for hydrological model parameterization of large scale afforested areas using remote sensing. – Physics and Chemistry of the Earth 27: 711-718.
[26] Joint Research Centre (ed.) (2000): Global Land Cover – Available via http://www-gem.jrc.it/glc2000/.
[27] Joint Research Centre (2004): European Soil Database (v 2.0), – European Soil Bureau Network and the European Commission, EUR 19945 EN.
[28] Klijn, J.A. (2002): Driving forces behind landscape transformation in Europe, from a conceptual approach to policy options. pp. 201-218. In: Jongmann, R.H.G. (ed.) The new dimensions of the European landscape. – Wageningen UR Frontis Series, Springer, Berlin.
[29] Kuntze, H., Roeschmann, G., Schwerdtfeger, G. (1994): Bodenkunde, 5th edition. – UTB, Verlag Eugen Ulmer, Stuttgart.
[30] Lehner, B., Döll, P. (2004): Development and validation of a global database of lakes, reservoirs and wetlands. – Journal of Hydrology 296 (1-4): 1-22.
[31] LIFE (ed.) (2007): Europe's wetlands – status and trends. – LIFE Focus: 3-11.
[32] Lyon, J. (2001): Wetland Landscape Characterization: GIS, Remote Sensing, and Image Analysis. – Ann Arbor Press, Chelsea, MI, USA.
[33] Matthews, E., Fung, I. (1987): Methane Emission from Natural Wetlands: Global Distribution, Area, and Environmental Characteristics of Sources. – Global Biogeochemical Cycles GBCYEP 1 (1): 61-86.
[34] Merot, P., Squividant, H., Aurousseau, P., Hefting, M., Burt, T., Maitr, V., Kruk, M., Butturini, A., Thenail, C., Viaud, V. (2003): Testing a climato-topographic index for predicting wetlands distribution along an European climate gradient. – Ecological Modelling 163 (1-2): 51-71.
[35] Miller, J., Franklin, J., Aspinall, R. (2007): Incorporating spatial dependence in predictive vegetation models. – Ecological Modelling 202: 225-242.

[36] Mitsch, W.J. (ed.) (1994): Global Wetlands: Old World and New. – Elsevier, Amsterdam.
[37] Moss, D., Wyatt, B.K. (1994): The CORINE Biotopes Project: a database for conservation of nature and wildlife in the European Community. – Applied Geography 14: 327-349.
[38] Moss, D., Davies, C., Roy, D. (1996): CORINE Biotopes sites-database. Status and Perspectives 1995. – Topic Report No 27/1996. Available via EEA: http://www.eea.europa.eu/.
[39] Moss, D., Davies, C. (2002 a): Cross-references between EUNIS habitat classification and the Habitats Directive. – European Topic Centre on Nature Protection and Biodiversity, Paris.
[40] Moss, D., Davies, C. (2002 b): Cross-references between the EUNIS habitat classification and the nomenclature of the CORINE land cover. – CEH project No. CC00389.
[41] Mulamoottil, G., Warner, B.G., McBean, E.A. (1996): Wetlands: Environmental Gradients, Boundaries and Buffers. – Lewis Publishers, New York.
[42] Nivet, C., Frazier, S. (2004): A review of European wetland inventory information. Report prepared in the framework of "A pilot study towards a Pan-European wetland inventory". – In: Taylor, A.R.D. and van Eerden, M. (eds.). Wetlands International (RAMSAR).
[43] Pott, R., Remy, D. (2000): Gewässer des Binnenlandes. – Ulmer, Stuttgart.
[44] RAMSAR Bureau. The Ramsar Convention on Wetlands. Key Documents. – Available via http://www.ramsar.org/index_key_docs.htm.
[45] RAMSAR Bureau (2008): The list of Wetlands of International Importance. – Gland, Switzerland. Available via http://www.ramsar.org.
[46] Sanderson, M.G. (2001): Global Distribution of Freshwater Wetlands for use in STOCHEM. – Hadley Centre Technical Note 32.
[47] Schneider, U.A., Balkovic, J., De Cara, S., Franklin, O., Fritz, S., P., Havlik, Huck, I., Jantke, K., Kallio, A.M.I., Kraxner, F., Moiseyev, A., Obersteiner, M., Ramos, C.I., Schleupner, C., Schmid, E., Schwab, D., Skalsky, R. (2008): The European Forest and Agricultural Sector Optimization Model – EUFASOM. – FNU-156, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg.
[48] Schultlink, G., Van Vliet, R. (1997): Wetland identification and protection: North American and European policy Perspectives. – Departement of Resource Development. Michigan State University. Available via http://rdservl.rd.msu.edu/wetlands/ wims/wims_nort.doc.
[49] Scott, J.M., Tear, T.H. (2007): What are we conserving? Establishing Multiscale Conservation Goals and Objectives in the Face of Global Threats. p. 494-510. – In: Lindenmayer, D.B., Hobbs, R.J. (eds.) Managing and Designing Landscapes for Conservation: Moving from Perspectives to Principles. Conservation Science and Practice Series 1, Blackwell Publishing, Oxford.
[50] Stillwell-Soller, L.M., Klinger, L.F., Pollard, D., Thompson, S.L. (1995): The Global Distribution of Freshwater Wetlands. TN-416STR. National Center for Atmospheric Research, Boulder, Colorado. – Available via http://www.scd.ucar.edu/iag/staff/lana/wetlands/.
[51] Succow, M., Jeschke, L. (1990): Moore in der Landschaft. Urania, Leipzig, Germany.
[52] Succow, M. and H. Joosten (eds.). 2001. Landschaftsökologische Moorkunde. – E. Schweitzerbert'sche Verlagsbuchhandlung, Stuttgart.
[53] Tsihrintzis, V.A., John, D.L., Tremblay, P.J. (1998): Hydrodynamic Modeling of Wetlands for Flood Detention. – Water Resources Management Journal 12 (4): 251-269.
[54] USGS (ed.) (1996): GTOPO30. – Available via http://www.edcdaac.usgs.gov/gtopo30/gtopo30.html.

[55] Verbyla, D.L., Litaitis, J.A. (1989): Resampling methods for evaluating classification accuracy of wildlife habitat models. – Environmental Management 13: 783-787.

[56] Walter, H., Breckle, S.W. (1999): Vegetation und Klimazonen (7th ed.). – Ulmer, Stuttgart.

[57] Walter, H., Lieth, H. (1967): Klimadiagramm-Weltatlas (3rd ed.). – Fischer, Jena.

[58] Walter, H., Walter, E. (1953): Einige allgemeine Ergebnisse unserer Forschungsreise nach SW-Afrika 1952/53: Das Gesetz der relativen Standortkonstanz; das Wesen der Pflanzengemeinschaften. – Berichte der Deutschen Botanischen Gesellschaft 66: 228-236.

[59] Wascher, D.M. (2000): Agri-environmental indicators for sustainable agriculture in Europe. – European Centre for Nature Conservation, Tilburg. ECNC Technical Report Series, Wageningen, The Netherlands.

[60] Wheeler, B.D., Shaw, S.C., Fojt, J., Robertson, R.A. (eds.) (1995): Restoration of temperate wetlands. – John Wiley & Sons, New York.

[61] Wiens, J.A. (2007): Does Conservation need Landscape Ecology? A Perspective from both sides of the Divide. p. 479-493. – In: Lindenmayer, D.B., Hobbs, R.J. (eds.) Managing and Designing Landscapes for Conservation: Moving from Perspectives to Principles. Conservation Science and Practice Series 1, Blackwell Publishing, Oxford.

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Impact of climate policy uncertainty on the adoption of electricity generating technologies

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ABSTRACT

This paper presents a real options model where multiple options are evaluated simultaneously so that the effect of the individual options on each other is accounted for. We apply this model to the electricity sector, where we analyze three typical technologies based on fossil fuel, fossil fuel with carbon capture and renewable energy, respectively. In this way, we can analyze the transition from CO_2-intensive to CO_2-neutral electricity production in the face of rising and uncertain CO_2 prices. In addition, such a modelling approach enables us to estimate precisely the expected value of (perfect) information, i.e. the willingness of investors and producers to pay for information about the correct CO_2 price path. As can be expected, the expected value of information rises with increasing CO_2 price uncertainty. In addition, the larger the price uncertainty, the larger are the cumulative CO_2 emissions over the coming century. The reason for this is that the transition to less CO_2-intensive technologies is increasingly postponed with rising CO_2 price uncertainty. By testing different price processes (geometric Brownian motion versus jump processes with different jump frequencies), we can also make useful recommendations concerning the importance of policy predictability. We find that it is better to have climate change policies that are stable over a certain length of time and change abruptly than less abrupt but more frequently changing policies. Less frequent fluctuations reduce the expected value of information and result in smaller cumulative CO_2 emissions.

1. Introduction

The current knowledge about climate change is plagued by uncertainties. There are major uncertainties about climate sensitivity and about the thermal lag of the climate system, see for example Roe and Baker (2007); Caldeira et al. (2003); Hansen et al. (2005); Forest et al. (2002) and Hansen et al. (1985). Further down in the causal chain there are perhaps even larger uncertainties about impacts both from low probability threshold events (O'Neill and Oppenheimer, 2002) and from gradual changes in the climate. However, as is conspicuously known, these uncertainties are not a reason for inaction, see for example Stern (2006); Yohe et al. (2004) and Azar and Rohde (1997) who all argue for policies in the near term, but based on a different line of reasoning. Rather, in line with United Nations Framework Convention on Climate Change (UNFCCC, 1992), the aim should be to act precautionary and with the intention of "*stabilisation of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.*" However, the way in which this political aim should be transformed into a more concrete formulation of climate targets is open to debate, both politically and scientifically.[1] In the end, this vague guiding principle of what constitutes a defensible long-term climate target adds an additional layer of uncertainty to the actual climatic uncertainties when deciding on what is a rational policy aimed at reducing GHG emissions in the short to medium term.

In addition to the above-mentioned uncertainties, there are also uncertainties about levels of future economic growth, population development, technological progress and the cost of reducing emissions below their baseline levels (see Riahi et al., 2007). These uncertainties make it even more difficult to decide on the level of policy response.

Moreover, what represents uncertainties for policy-makers is not the same as what makes up the uncertainties for the agents

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[1] However, many analysts and policy-makers argue that a reasonable long-term target is a maximum global average surface temperature change of about 2 °C above the pre-industrial level, see for example Azar and Rhode (1997); European Union (2005); Graßl et al. (2003); Oppenheimer and Petsonk (2005).

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that will actually implement the change of emission levels, here called investors. The investors are not just facing all the uncertainties that the policy-makers face, but also the uncertainties of the actual policies themselves.

The policies aimed at reducing emissions may frequently and unexpectedly be changed for a number of reasons, e.g. change of governments, collapse of the international cooperation of reducing GHG emissions, arrival of new information about climate sensitivity, etc. It is obvious that many long-term policy plans have changed over the course of time. Such policy changes or failures are clear indications of the danger of the lack of credibility in long-term planning (see e.g. Helm et al., 2003). Ultimately, this enhances the uncertainty faced by investors.

In this paper, we focus on how investment decisions in the electricity sector are affected by future CO_2 price uncertainty. The choice for an investor in the electricity sector as a unit of analysis is motivated by the fact that electricity still represents the major contribution to overall emissions, and is also projected to continue doing so over the coming decades, see for example CAIT (2007) for the historical contribution and the GGI Database, International Institute of Applied Systems Analysis (2007) for projections.

Moreover, since capital investments in the electricity sector are largely irreversible and will consequently be decisive for the future energy mix, it is important for policy-makers to understand how their policies influence the investor's decision-making. If policies lack long-term credibility or are surrounded by uncertainty there is a risk that producers and investors refrain from undertaking the necessary investments, so that the policy aims cannot be met at lowest possible cost. To summarize, there are three important features of our problem, which make the application of real options modelling (Dixit and Pindyck, 1994) appropriate: (1) flexibility on behalf of the investor (e.g. invest immediately or wait until uncertainty has been resolved) and producers (e.g. switch the carbon capture module off when CO_2 prices are temporarily low); (2) uncertainties pervading the future path of the CO_2 price; and (3) large sunk costs involved in building power plants, which make most investments irreversible.

Investment into power plants has been analyzed in real options frameworks before, where a distinction has to be made between models that are occupied with operational options focusing on the load profile, for example, and models targeted at long-term planning, where the time horizons are 30–50 yr instead of a day with hourly loads. Frameworks in the first category include Tseng and Barz (2002) and Hlouskova et al. (2005) and Deng and Oren (2003) amongst many others. Real options studies focusing on long-term planning are e.g. Fleten et al. (2007); Laurikka (2007); Laurikka and Koljonen (2006); Reinelt and Keith (2007) and Reedman et al. (2006)—all of which are also concerned with uncertainty about electricity, fuel and/or CO_2 prices. The above-mentioned article by Reinelt and Keith (2007) comes closest to the framework developed in this paper. They also value options of installing several different technologies in one and the same framework. Also in the vein of our work, Buchner (2007) stresses the impact that the length of the commitment period might have on investment decisions. She presents results from an IEA study using a real options framework showing that the value of postponing investment in carbon capture equipment is reduced when the commitment period is longer, which we can confirm in the results of this paper. Madlener et al. (2005) set up a dynamic technology adoption model to incorporate series of vintages of multiple technologies, but they explicitly borrow elements from real options theory as well.

Our work falls into the category of long-term planning models. However, since we want to investigate how climate change policy shapes the transition from one technology to another–which is potentially less carbon-intensive—we look at a much longer time horizon (150 years) than the above-mentioned models, which range between 30 and 50 years. Moreover, we not only consider the effect of CO_2 price uncertainty, but we also investigate how different price processes affect the investment pattern and thereby the transition. The reason why different price processes are used is that CO_2 prices may either be raised continuously with only small fluctuations, like an escalating and continuously adapted CO_2 tax or rising permit prices, or they may follow a more stable path for a specific period of time without fluctuations and may then be adjusted more drastically, as a new commitment period begins or new information about climate sensitivity becomes available, for example. Hence, one can see the time periods between the price jumps as a simple representation of Kyoto style commitment periods. We are interested to see how the time length between the jumps affects the decision of the investor, the expected value of information and–potentially–the value of better information in terms of cumulative CO_2 emission savings, which might be an important guideline for policy-makers striving for CO_2 reductions.

In the area of climate change policies, several studies have analyzed the expected value of information, see e.g. Peck and Teisberg (1993); Manne and Richels (1992); Nordhaus and Popp (1997). The general approach in these papers (the work by Manne and Richels (1992) is an exception) is to adopt a cost benefit approach with the aim of finding the optimal policy response to climate change damages and to estimate how much the world would be better off economically if, for example, climate sensitivity and the level of economic damages were known; see Peck and Teisberg (1993) and Nordhaus and Popp (1997). The resolution of uncertainties is generally treated in a very simplified manner using multi-stage optimisation where all information about the correct level of the uncertain parameters is obtained after one time period; see for example Manne and Richels (1992) and Nordhaus and Popp (1997). Some others, most notably Reinelt and Keith (2007), adopt an approach similar to the one used in this paper, i.e. stochastic dynamic programming. This approach enables a much richer description of the evolution of the uncertain parameters but with the drawback of having much less scope in terms of controls and states.[2]

To summarize, the main aims of this paper are to analyze (1) the impact of persistent CO_2 price uncertainty on investment decisions for less CO_2-emitting electricity generating technologies and (2) the expected value of information and the expected cumulative CO_2 emission savings from having information depending on different levels of CO_2 price uncertainty and the frequency of policy changes (or, as said, a simple representation of commitment period length).

The last point is related to the issue of credibility of optimal plans and to the issue of how often policies should respond to changes in information about the underlying parameters (in our case, this refers to the information about climate change impacts and costs of abatement that should determine the welfare-maximising CO_2 price, for example). The shorter the time frame for the policy, the closer the policy could be to the updates in, for instance, relevant scientific information or major technological breakthroughs. This would result in more frequently changing policies, which is in opposition with the industry's plea for long-term

[2] Multi-stage optimisation becomes computationally intensive with an increasing number of periods and scenarios, because it requires decision-making at each stage depending on the prior sequence of states. Stochastic optimal control problems like ours suffer from similar dimensionality problems when there are many possible states or controls. However, our study investigates a long-time horizon (150 years) and has a relatively modest state and control space, so multi-stage optimization is not the optimal choice for our problem. Cheng et al. (2004) compare the two approaches in more detail.

predictability of policies aimed at inducing investments in the corresponding technologies, see for example International Chamber of Commerce (2007). We do not aim to find the optimal length of time periods between policy changes (as a e.g. indicated in Buchner (2007), where this is computed to be in between 10 and 15 yr); rather, we study the cost to investors of having polices that change unexpectedly over time.[3]

2. Multiple real options in electricity investment

2.1. The model

This model is intended to determine the optimal investment plan for a single cost-minimising electricity producer (or planner), who has to produce a specific amount of electricity, but faces stochastic CO_2 prices. Furthermore, the possibility of waiting for revisions of the climate change policy and its potentially significant impact on CO_2 taxes or emissions prices affects the timing of investments. By studying these aspects in our model, we can determine the effect of commitment to a particular policy on investments. A real options framework is especially suited for this purpose, because it precisely values benefits of acquiring information by waiting.

In this section, we will explain the model structure in detail and derive the mathematical formulation of the problem. It is important to note that valuing all these options in one and the same framework implies that the value of the individual options–both the options to invest and the operational options–will be influenced by the presence of the other options in the model. In other words, the options become interdependent; an important feature that we have to bear in mind when interpreting the results. The framework in this paper is, therefore, different from many existing models that value different options independently of each other and then compare the option values.

The planning horizon of the model is 150 yr. The producer (or planner) has a number of options at his disposal for producing a specific amount of electricity.[4] In the first year the producer has to determine, which plant to invest in: this is either a coal-fired power plant, which can include a carbon capture and storage (CCS) module, or a wind farm. Further, if a coal-fired power plant is installed in the first year, the investor has the possibility to retrofit the plant with a CCS module later on or to invest in a wind farm eventually. It is important to note that all of these investments involve large sunk costs and are, therefore, associated with a high degree of investment irreversibility.

The uncertainties that we consider for the cost-minimising electricity producer are future CO_2 prices. Note that this CO_2 price uncertainty influences only the production cost of the coal-fired power plant both with and without the CCS module. More specifically, we analyze two different stochastic processes for the CO_2 price path: first, we implement a geometric Brownian motion (GBM), which mimics relatively small fluctuations in the upward-trending CO_2 price, which could be due to the trading of CO_2 permits or small adjustments to an escalating tax on CO_2 emissions. Second, we investigate the investment response when using a price process that also exhibits an upward trend. However, there are no continuous fluctuations as in the GBM, but (randomly sized) jumps occurring at a predefined frequency, which bring the CO_2 price to a new level in a much more abrupt way than in the case of the GBM. This analysis will, therefore, serve to shed some light on the debate whether more frequent adjustments leading (at the extreme) to continuous fluctuations in the price of CO_2 should be preferred over a more stable trend, which is adjusted less frequently but instead more drastically. Also, there are other costs that influence the optimal investment plan, which are not treated as uncertain. The cost of capital is taken to be constant and deterministic, which ignores the possibility of technical improvements. However, we omit this on purpose, since our focus is on properties of CO_2 price uncertainty and results should not be obscured by interaction effects. For the same purpose, we abstract from the stochasticity in fuel prices and operations and maintenance (O&M) costs. Also, we ignore differences in construction times. Since our model is designed for the very long run, this omission does not change the qualitative results, as we have verified. Moreover, capital is not divisible in this model. This implies that the investor has the choice to invest either into the complete coal plant (with or without CCS module) or into the wind farm that produces the same amount of electricity, or to stick to the current technology.

As stated above, we have chosen both a GBM and a jump process to simulate the CO_2 price development. Current price projections clearly foresee an upward trend, but with a very large spread for the long-run values (see e.g. Fig. 2). In the case of a GBM, the price path can be characterised as

$$dp_t^c = \mu \cdot P_t^c dt + \sigma P_t^c \cdot dW_t^c \tag{1}$$

where μ is the drift parameter, σ is the volatility parameter and $dW_t{}^c$ is the increment of a Wiener process.

We assume that the effect from uncertainty when CO_2 prices are continuously adapted can be captured by varying the values for σ in Eq. (1). In the experiments that we will conduct in Section 4, we investigate what happens to the investment when the CO_2 price follows the trend μ, but where we test for a large range of σ.

In addition, we want to analyze the effect of polices changing less frequently than in the case of the GBM in Eq. (1). What we model is that–when the policies change–the CO_2 price jumps to a new level and continues to follow a deterministically growing price path at this new level, until the policy changes again after a predefined number of years, and so on. The new price level is determined by a random jump. The size of jumps are drawn from an underlying GBM, meaning that, at the actual date of the policy change, the price jumps to a level determined by a process that has followed a GBM, since the last policy change. By modelling the policy updates in this way, we can filter out the effect of having less frequently changing policies from other disturbances that we would have introduced by using a totally different stochastic price process, for example a Poisson process. Therefore, the results from the two exercises become comparable, as both the mean price of two processes (GBM and jump process) and their variance in the time step, when the samples are drawn, are the same. The two price processes considered are shown in Fig. 1.

The investor has to decide what plant to install in the initial year and then optimises the possible timing of investing in other technologies, so that the sum of discounted expected future costs is minimised. The yearly cost Γ consists of the cost of producing (and importing in the case when the CCS is used, see Section 3) electricity including annual O&M and fuel costs, the payments for CO_2 emissions and costs associated with an action, $c(a_t)$. Since we implicitly have a constraint that a specific amount of electricity has to be produced, we can assume that the installed plant will run continuously and thereby produce a fixed amount of output for a fixed amount of inputs per year.

[3] Note that we do not study the interaction effects between the policy-maker and the investors, see for example Tarui and Polasky (2005) for an interesting study about this interaction in the context of environmental regulation.

[4] We abstract from growth in demand and assume that the installed capacity stands during the whole planning period. The installed capacity in the model could also be interpreted as a representation of the dominating technology in an electricity supply system rather than as a single plant.

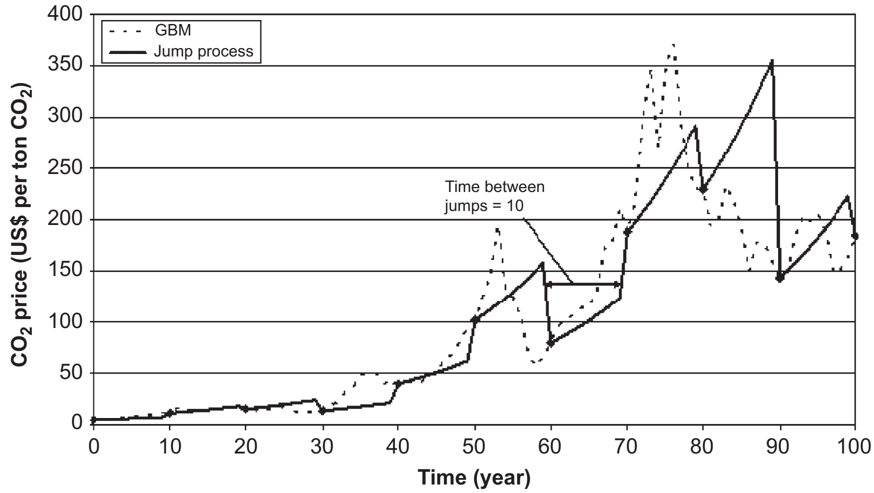

Fig. 1. Compared price processes for the case when the time between the jumps is 10 yr. The diamonds indicate when the jump process takes a sample of the underlying Geometric Brownian motion.

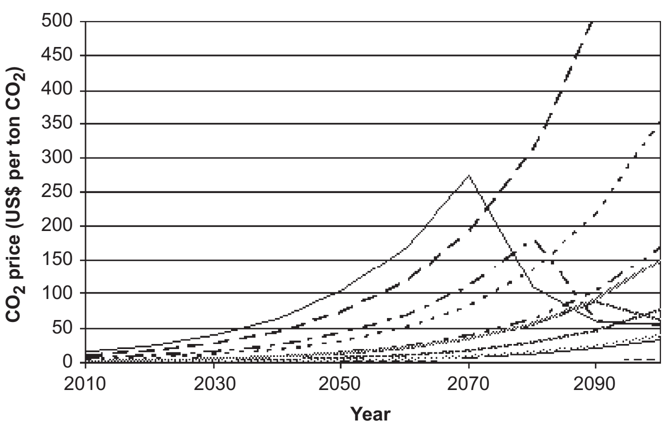

Fig. 2. CO_2 (shadow) prices (source: GGI Database, IIASA, 2007).

In the problem formulation, x_t denotes the state that the system is currently in at time t, i.e. whether the coal-fired power plant, the CCS module and/or the wind farm has been built so far, and which plant has been running. a_t is the control variable, or more precisely the action undertaken in year t.[5] As x_{t+1} depends only on the current values of the action and the state, x_{t+1} is a function of x_t and a_t, where a_t is an element from the set of feasible actions.[6] The yearly costs are

$$\Gamma(x_t, a_t, P_t^c) = q^c(m_t) \cdot P_t^c + q^f(m_t) \cdot P^f + OC(m_t) + c(a_t) \tag{2}$$

where P^f is the price of coal, OC is the operational cost per year that also includes the costs of transporting and storing the carbon from the operation of the CCS module, the q refer to annual quantities of CO_2 and fuel, respectively, and m_t denotes the type of power plant that is operational at time t determined by the state and action, (x_t, a_t). Note that $c(a_t)$ is the cost of an action, i.e. basically capital costs. However, the investor in this framework does not bear all costs of an action at once, but the capital costs are annualised, so that the payment is spread over the planning horizon. Even if the plant is abandoned in favour of another one, these payments must be made, which can be interpreted as a loan that has to be repaid including interest.

Moreover, the investor knows that the CO_2 price follows a stochastic process with a known starting value, drift and volatility. The investor's problem is now to determine the optimal investment strategies $\{a_t\}_{t=1}^{T}$, where $T = 150$ is the planning horizon. The optimal decision in each year can be computed recursively by solving the following Bellman equation:

$$V_t(x_t, P_t^c) = \min_{a_t \in A_t(x_t)} \{\Gamma(x_t, a_t, P_t^c) + e^{-\beta} \cdot E[V_{t+1}(x_{t+1}, P_{t+1}^c) | P_t^c]\} \tag{3}$$

where $A_t(x_t)$ is the set of feasible actions for a given state x_t and β is the discount rate. Note that the right-hand-side of the Eq. (3) can be split into the sum of the immediate costs, $\Gamma(x_t, a_t, P_t^c)$ and the continuation value, $e^{-\beta} \cdot E[V_{t+1}(x_{t+1}, P_{t+1}^c)|P_t^c]$, which depends on the options exercised. This implies that the model explicitly takes into account path-dependency, which is especially important and interesting in the investigation of transition dynamics. We will see later that such path-dependency makes technologies dependent on variables that they are individually not linked to.

2.2. Methodology

In order to compute the continuation value, we use Monte Carlo simulation. The approach is relatively easy to extend and remains efficient even for relatively complex problems.[7]

The solution of the recursive optimisation part is a multi-dimensional matrix containing the optimal action a_t for every time period, state and price, i.e. offering a kind of "recipe" for all future contingencies. To obtain the final outcome, we simulate 10,000 possible CO_2 price paths and extract the corresponding decisions from the output, thereby generating frequency distributions of decisions as e.g. optimal investment times.

When calculating the expected value of information and the expected cumulative CO_2 emission savings from having information, we use the 10,000 simulated CO_2 price paths and two model approaches. Hence, we use both the stochastic dynamic programming model described above and a deterministic dynamic

[5] Possible actions are: building the coal-fired power plant, the CCS module or the wind farm, and switching between the previously built technologies.

[6] Adding the CCS module to an inexistent coal-fired power plant is an example of an action, which is not feasible.

[7] We have also tested the method of using partial differential equations, which has ultimately delivered the same result as the Monte Carlo approach. The approach taken for solving the problem is the same as in Fuss et al. (2008), which the reader is referred to for more detailed information.

Table 1
Technology characteristics based on IEA (2005, 2006).

	IGCC	Add-on CCS	Wind
Capital cost (US$/ kW)	1300	350	1250
Fuel cost (US$ per GJ_{heat} LHV)	1.7	1.7	NA
Conversion efficiency (% LHV)	50	44	NA
CO_2 emissions (ton C/GJ_{heat} LHV)	0.0275	0.00275	NA
CO_2 storage cost (US$/ton C)	NA	20	NA
Capacity factor (%)	75	75	25

programming model, where the evolution of each of these 10,000 price paths is known ex ante. The results from both these models are compared and the value of information can be calculated. Technically, this means that the 10,000 price paths simulated for the stochastic model are saved and then used for the deterministic version, i.e. there are also 10,000 instances of decisions in the deterministic model, with the difference that investor knows the price path on beforehand in the deterministic case. By comparing the average NPV costs and the expected cumulative CO_2 emissions in the stochastic case, with those of the deterministic case (with 10,000 identical CO_2 price paths), we obtain a measure of the uncertainty effect–or the lack of information–that has kept the investor from finding the same optimal strategy in the stochastic cases as in the deterministic cases, and thereby measure the expected value of information. The expected value of information is estimated in relative terms based on the cost of the policy. Thus, it is the difference in extra technology costs due to the CO_2 policy and CO_2 payments that are compared in the stochastic and deterministic cases.

3. Technology data

There are three technology options considered in the model. These technologies are chosen to represent a wider range of possible technologies. The technologies we consider are (1) a coal-fired power plant, in our case an integrated gasification combined cycle (IGCC) plant, (2) the option to retrofit this plant with a module that captures the carbon, and which includes the necessary infrastructure to transport the carbon to a "safe" storage, hence a CCS module and (3) a wind farm. These three technologies can be seen as representative technologies of the current system, an intermediate change in the current system and a radically new system, where the latter features high capital costs.

The characteristics of technologies considered are chosen to be in line with current and future estimates of the performance and cost of these technologies (see Table 1). An important simplification that has been made in the model is that the lifetime of each plant is not accounted for. Hence, we implicitly assume that the maximum lifetime of each plant is equal to the planning horizon. However, in most instances in the results, plants are used for a shorter period of time, since as CO_2 prices increase, the coal power plant and in most instances also the plant with CCS are phased out. The lifetime assumption simplifies calculations, even though the qualitative aspects of the results would most likely not change substantially, if dropped.[8] Also, the focus and novelty of our analysis is not on individual plants per se, where lifetime differences could admittedly be important, but on analyzing the transitions from one energy technology "regime" to another. In a similar line of reasoning, our plant lifetime assumption could be interpreted such that in each simulation each technology represents a rough characterisation of the dominating technology in terms of the share in the total capacity of a country or region.[9] Note also that the physical lifetime of power plants are often much longer than what is usually classified as the economic lifetime, see e.g. Lempert et al. (2002).

As described above, the model is formulated as a stochastic cost-minimisation problem given that a specific amount of electricity has to be produced. Since the IGCC plant retrofitted with CCS will produce a smaller amount of electricity than the IGCC plant without CCS, we assume that, when the CCS module is used, electricity is imported from an external source to ensure that the required amount of electricity is generated. For the imported electricity, we assume that the price of such imports rises with increasing CO_2 price. The pass-on of the CO_2 price to the electricity price is estimated from the IIASA GGI Database (International Institute of Applied Systems Analysis, 2007). The following relationship is used in the model:

$$P_{electricity} = 48 + \min(36, 0.63 \cdot P_{CO_2}^{0.837}) \tag{4}$$

where $P_{electricity}$ is given in US$ per MWh and P_{CO_2} is given in US$ per ton CO_2. We also assume that the pass-on of the CO_2 price to the electricity price does not continue indefinitely; instead the electricity price does not increase beyond 84US$ per MWh. The reason for this is that beyond a particular CO_2 price level (about 130 US$ per ton CO_2 in the data we have used) carbon-neutral sources of electricity become increasingly attractive and set an upper level on the impact of CO_2 prices on the electricity price. This is in line with results presented in the GGI Database.

For comparison, an old coal-fired power plant would result in a linear pass-on equal to about 1 on the margin, while a new natural gas combined cycle (NGCC) plant would result in a linear pass-on equal to about 0.4 on the margin.

Furthermore, the trend and the volatility of the CO_2 price process have to be calibrated. As is well founded in the economic theory, the efficient CO_2 price should rise over time, if the ultimate aim is to eventually stabilise the climate. Since the overall aim of the UNFCCC (1992) is the stabilisation of the climate at a level "*that would prevent dangerous anthropogenic interference with the climate system*" and the European Union (2005) has interpreted this as stabilisation of the anthropogenic temperature change below 2 °C above the pre-industrial level, a growing CO_2 price appears to be justified.

The CO_2 prices used in the simulations are based on the projections for GHG shadow prices taken from International Institute of Applied Systems Analysis (2007), see Fig. 2. These prices are dependent on the future economic growth, technology development, stabilisation target and population growth. In addition to the uncertain evolution of these factors, we seek to include the uncertainty originating from changing policies in the price processes used to simulate the evolution of the CO_2 price. These are modelled as a GBM and a jump process, respectively (see previous section). Note also that the prices obtained from the GGI Database are deterministic and should only be seen as rough indications of how future CO_2 prices may evolve. The growth rate is about 5% in all scenarios although with different starting prices. We adopt an expected growth rate of 5%, i.e. $\mu = 0.05$, an initial CO_2 price of 5 US$ per ton CO_2 and test for a range of different levels (0–30%) of the volatility parameter σ.

[8] One way of handling a shorter lifetime of e.g. wind power capacity, would be to increase its maintenance costs, if the technical lifetime would be exceeded. Since this does not happen in the majority of simulations, however, and since the pattern of transition would still be from coal over CCS to wind, we postpone such questions for further research.

[9] In applications where the exact installation timing of specific, individual plants should be estimated, it would of course be necessary to consider the difference in plant lifetimes, if these are significant.

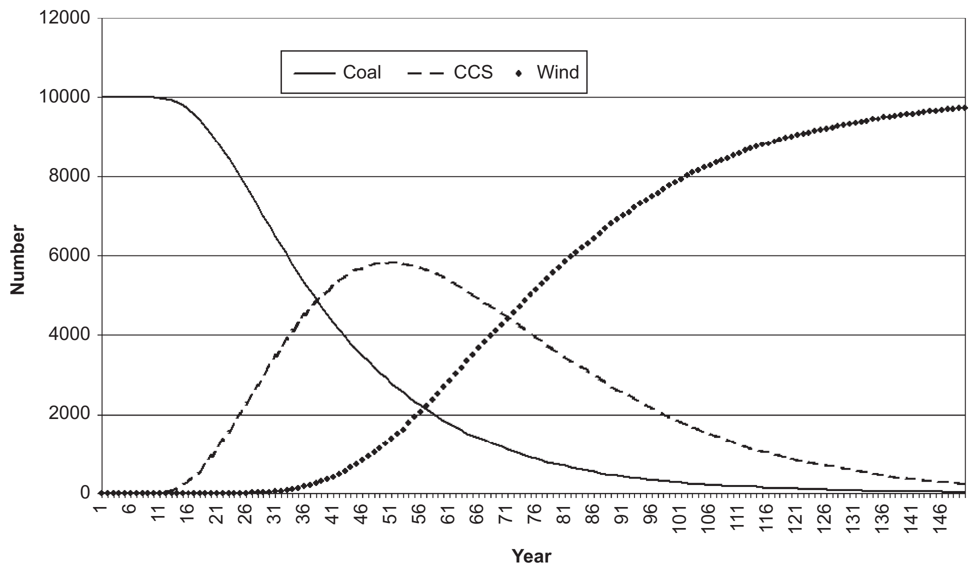

Fig. 3. Frequency distributions of investment in the coal-fired power plant (solid line), CCS (dashed line) and the wind farm (circles) over time (with $\sigma = 0.14$).

4. Results

As has been mentioned above, the outcomes of our modelling framework are frequency distributions of (investment and operational) decisions. By studying these frequencies over time, we can analyze the transition from one technology to the next one, see Fig. 3. The *y*-axis represents the number of simulations of price paths, i.e. the maximum number of times that a technology can be invested in is 10,000.[10] We observe that in the first year the coal-fired power plant is always installed. The reason is simply that it is the technology with the lowest cost for producing electricity. Over time, i.e. when CO_2 prices are higher, adding the CCS module becomes more and more attractive, resulting in more frequent investment into the module. Only when the CO_2 price has risen to a relatively high level (to about 100$/ton of CO_2 or higher), the wind farm is built more frequently.

Furthermore, it is interesting to compare the frequency distributions obtained from the stochastic model with the one from the deterministic model, where the price paths are known ex ante, see Fig. 4. The divergence between the results of the two models points to the fact that there is a value of knowing the price development on beforehand, i.e. the expected value of information is positive.

An interesting result is that wind is built in the beginning of the model's time horizon in more than 15% of the cases in the deterministic framework (where the price paths are known on beforehand), whereas in the stochastic case coal is always chosen. This can be interpreted as a kind of hedging strategy (in the stochastic case) on the part of the investor, since he can never be certain what the CO_2 price will be. In the stochastic case, the price could turn out to be low and then the investor/producer would not want to have to rely on wind. The possibility to add the CCS module strengthens this effect. The CCS module thus offers a certain extent of flexibility to the coal-fired power plant owner that allows him to save a large amount of emissions without being obliged to incur the much higher capital costs that a transition to wind power would require. Observe also that CCS is chosen more often in the middle of the planning period when CO_2 prices are stochastic. The reason for this is that once the electricity producer has invested into the coal power plant, it is less costly, for medium to high CO_2 prices, to switch to the CCS plant than to invest in the wind directly. This flexibility reinforces the path-dependency due to the option values' dependency on the existence of other options. Note also that after year 77 wind is chosen more often in the stochastic case than in the deterministic case, hence the opposite result compared to the first 76 yr. The explanation for this is that in the stochastic case investments are exercised based on expectations of future prices, while in the deterministic case, investments rely on actual future prices. As a consequence, trigger prices are reached in some cases inducing investment into wind in the stochastic case, while in the deterministic case no investment into wind is made, since in these cases the CO_2 prices are known to drop in the subsequent years.

Another interesting point is that the presence of the option to add CCS delays the transition to wind. If the coal-fired power plant was not flexible in this respect, wind would be phased in much earlier. However, in terms of cumulative emissions, this does not make as big a difference as one might suspect. In fact, coal would be kept longer before wind would be adopted, so this increases the emissions in the first half of the planning period, which were previously lower because of the CCS module. The earlier introduction of wind makes up for this negative effect, but the ultimate difference is not substantial. This implies that CCS is a valuable possibility to "bridge" the transition from fossil-fuel-based electricity generation to renewables.

With respect to the expected value of information, we have estimated the difference in average costs between the stochastic and the deterministic model for σ ranging from zero up to 30%. A positive value of information indicates that it is beneficial to have more precise information about the CO_2 price development. From Fig. 5 it is clear that the value of information of future carbon prices is positive and increases with rising σ.[11]

[10] Please note that what is represented in Fig. 3 is not the number of plants actually installed, but the number of simulations (of CO_2 price paths), for which the plant/technology in question was chosen. So the curves can actually be interpreted as some sort of frequency distribution arising from the development of CO_2 prices.

[11] While raising σ represents the case where there is uncertainty about CO_2 prices, it is also important to note that the level of the trend, μ, plays an important role as well: with a very low μ, the decision to invest into less carbon-intensive technologies may never be triggered at all, given that the CO_2 price starts at the same level as assumed throughout the paper. Likewise, an expected change in the sign of the trend–due to e.g. the possibility of failure of climate policy negotiations–will raise the option value of waiting tremendously and lead to postponement of investment into CCS and wind energy (see Fuss et al. (2008) for such an analysis of uncertainty about the trend).

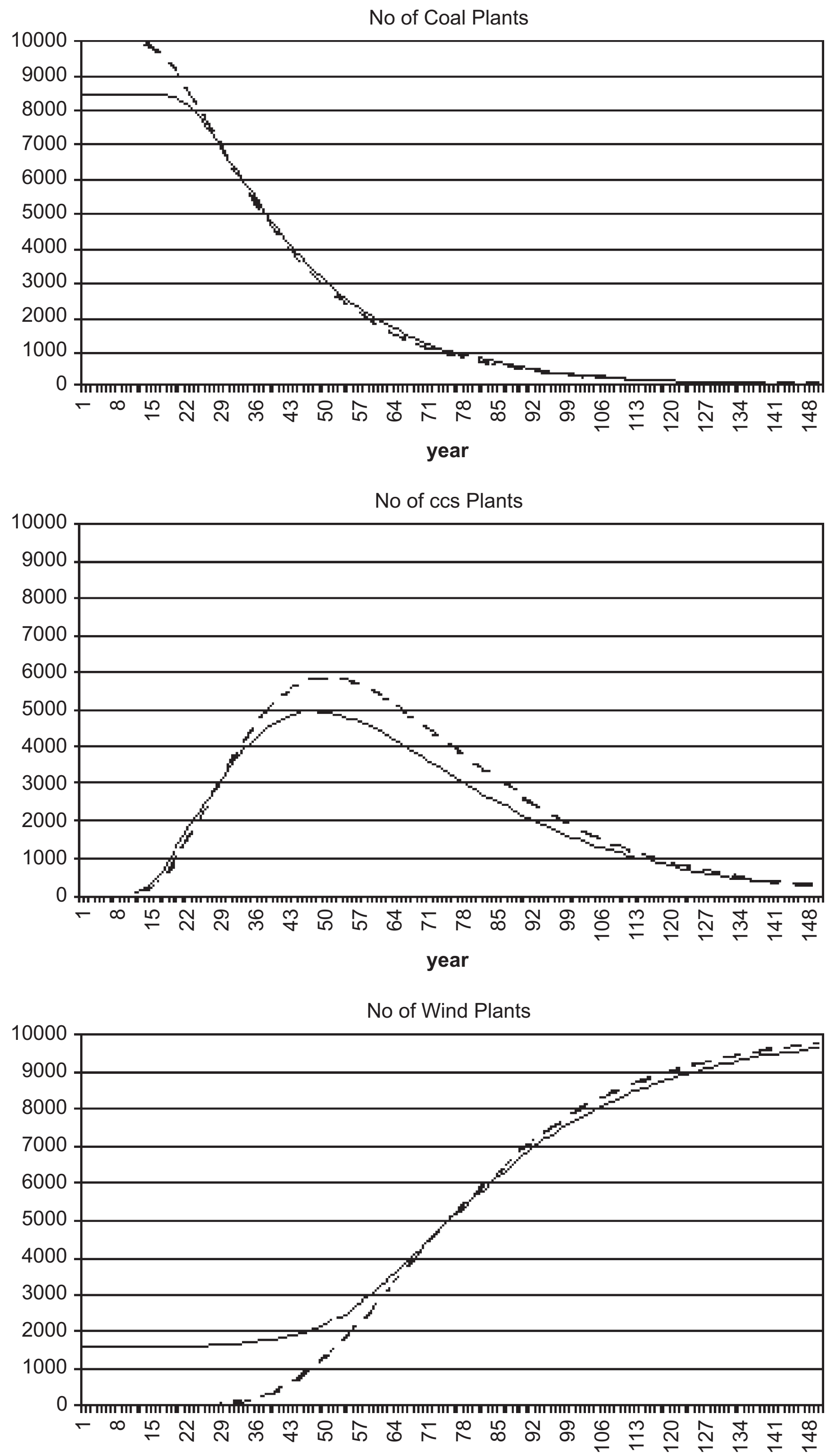

Fig. 4. Deterministic (solid line) and stochastic (dashed line) frequency distributions of investment into coal-fired capacity, CCS and wind energy (top to bottom) over time (with $\sigma = 0.14$).

The expected value of information can be interpreted as the willingness of the investors to pay in order to have perfect information about the future evolution of the CO_2 price. On average, this willingness to pay for information is about 1 US$ per MWh for levels of σ about 20%.

As mentioned earlier, one of the major differences in our modelling approach compared to what many have used in the existing literature is that we value the options in the presence of each other. This is important, since the existence of one option will influence the value of another—an impact which is neglected

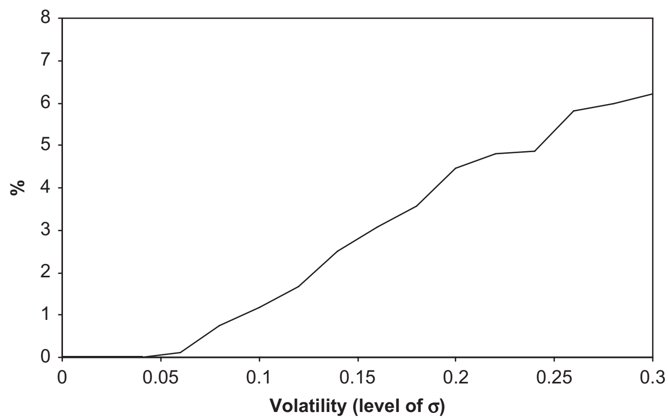

Fig. 5. Relative expected value of information in monetary terms for increasing CO_2 price volatility with continuous fluctuations (GBM) (this represents the fraction that an investor would be willing to pay in order to know the price path ex ante).

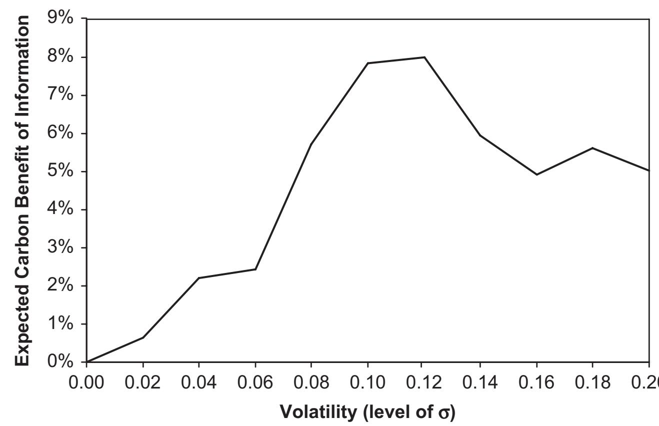

Fig. 7. Expected cumulative CO_2 emission savings from having information for increasing CO_2 price volatility with continuous fluctuations (GBM).

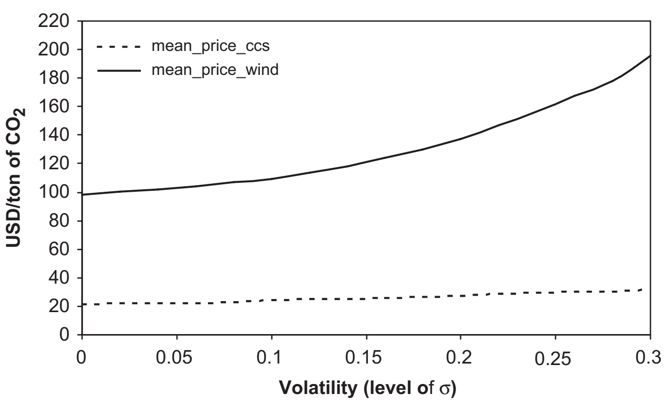

Fig. 6. Average trigger price per technology.

when valuing options independently of each other. As an example, consider the option to invest in wind. Individually, the value of a wind farm does not depend on the CO_2 price and the volatility surrounding it, since it does not represent a cost to the wind farm owner. However, the fact that the investor in our framework starts out by building a coal-fired power plant implies that there is also a value of holding on to the existing capacity, which will in turn influence the decision to install the wind farm. This can be observed in Fig. 6, where we show the average trigger price of investing in wind (solid line) and CCS (dashed line). The trigger price is that level of the CO_2 price, at which investment into a particular technology becomes worthwhile; in other words, when investment is triggered. It is clear that the trigger price required for investment in wind increases as uncertainty–in the form σ–rises, because the option to keep the coal plant operational is larger when the CO_2 price is less predictable. The trigger price of installing CCS is also affected positively by CO_2 price uncertainty—but to a much lesser extent, since it is much less costly in terms of capital costs. To summarize, in our framework with multiple options, more uncertainty leads to a postponement of investment into wind and CCS, hence one is locked into existing technologies, in this case coal-based generation technologies. As a consequence of this, one may conjecture that less uncertainty would reduce overall, cumulative CO_2 emissions.

In order to shed some light on this question, we compute cumulative CO_2 emissions under different levels of uncertainty–both in the stochastic and the deterministic model–and analyze the relative difference in the CO_2 emissions in these two model settings. As can be seen in Fig. 7, perfect information about future CO_2 prices would lead to less cumulative CO_2 emissions. Even though our hypothesis is validated by the positive relationship between the fraction of cumulative CO_2 emissions that would have been saved under certainty (compared to the stochastic case), the results are less clear-cut for large levels of σ. The reason for this is the finiteness of the planning horizon. If the time horizon of the model would have been longer than 150 yr, the line in Fig. 7 would continue to slope upwards beyond $\sigma = 10\%$. The explanation for this is that the producer still has both the coal-fired power plant and the CCS module operational at the end of the planning period and the higher the volatility, the more often the trigger price for investment into wind will not be reached.

The second major focus of this paper is on how the expected value of information and the expected cumulative CO_2 emission savings from having information depend on the frequency with which policies are changed. As previously discussed (see Section 2.1), we have assumed that policies are changed after predefined time steps, e.g. representing the length of Kyoto style commitment periods, which would be five years, but longer periods are also tested for.

We find that frequently changing policies are more costly for investors/producers than policies that change only seldom, see Fig. 8. Hence, for a GBM with $\sigma = 20\%$, the expected value of information is above 4% if the policy is changed randomly every year (which is basically the case of a GBM), compared to only about 1.5%, if random jumps are only passed on to the investors every 15th year. The main reason for this result is that the investment decisions in our stochastic model get more similar to those of the deterministic model in our 10,000 Monte Carlo runs in the sense that the same technologies are chosen at the same time step more frequently. (Fig. 9)

In the stochastic case, the decision to invest is usually postponed to the date of the price jump or to the subsequent years after a price jump. The reason is that the option value of waiting for the next price jump increases as the new jump is approached. Just after a jump has occurred, this option value of waiting for a new jump falls drastically. Even though this mechanism is not present in the deterministic model, the results become more similar, as the intervals between price jumps grow larger.

Similarly, we find that the expected cumulative CO_2 emission savings from having information also drops with decreasing frequency of the policy change. This follows from the fact

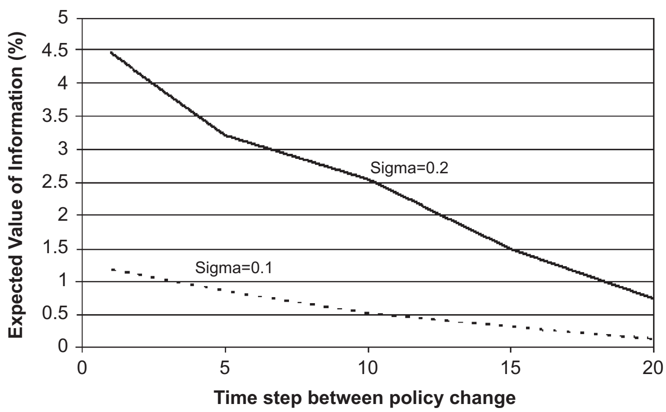

Fig. 8. Expected value of information for investors (plotted over the time step (years) between policy changes).

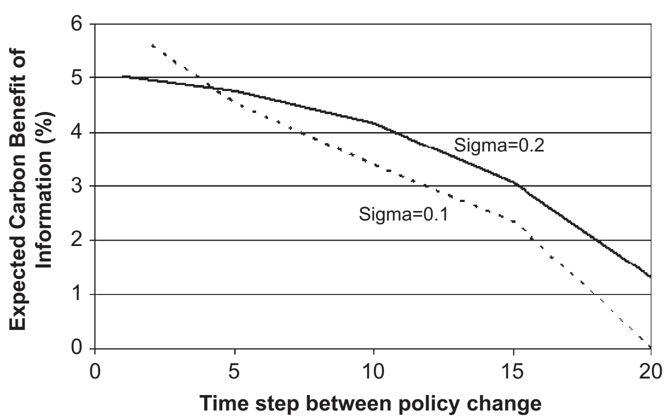

Fig. 9. Expected cumulative CO_2 emission savings from having information (plotted over the time step (years) between policy changes).

explained above that the results from the runs of the stochastic model become more and more similar to results of the deterministic model for a lower frequency of policy jumps. Also, in line with the basic GBM case, the expected cumulative CO_2 emission savings from having information are rather similar for $\sigma > 10\%$.

5. Discussion

As has been alluded to in the last section, it is important to note that the results shown above depend on the type of price process and technology characteristics assumed. However, we think that an escalating CO_2 price is a realistic representation and it is well founded in economic theory that the price should rise if the ultimate aim is the eventual stabilisation of the temperature or the concentration of greenhouse gases. Concerning our technology assumptions, they are in line with contemporary scientific literature. Our main simplifying assumption is that we have assumed that the power plants have a lifetime extending over the whole planning horizon and that the producer can switch back to previously installed plants e.g. to coal-fired capacity, when he/she has been using CCS or the wind farm previously. In reality, such switches would be costly[12] and the old capital would eventually deteriorate. However, including these features in our framework will most probably not change the quality of the conclusion derived from the simulation results presented in the paper, although the exact numerical values would be different. However, exact numerical values are not what we are aiming for in this study.

With these caveats in mind, we can then turn to analyze the policy implications of the results. The main lesson to be learned from our experiments is that it is better to change the expectedly growing CO_2 price less often and in a rather drastic manner compared to more or less frequently changing CO_2 prices. Hence, it is better, in terms of the expected value of information and the expected cumulative CO_2 emission savings from having information, to have infrequent but large price jumps compared to frequent and small price jumps. The expected value of information and the expected cumulative CO_2 emission savings from having information drop, as the time steps between policy updates increase. This result is relevant for the discussion concerning the time length of commitment periods in Kyoto style climate regimes. Even though permit prices may fluctuate for a range of different reasons within commitment periods, large jumps in permit prices can be expected when announcing a new commitment period with a change in the negotiated emissions targets.

In addition, policies targeted at supporting CCS technology or wind energy (in addition to "punishing" coal-fired capacity owners by levying carbon taxes or introducing permit trading) can take several forms: for example, funding of R&D has the potential of decreasing capital costs and raising production efficiency, or investors considering less carbon-intensive technologies can be granted subsidies directly. Regardless of the precise form of support, the effect will be that investment in the supported technologies will become attractive at an earlier date, i.e. the frequency distributions of CCS and wind in Fig. 3 would shift to the left. However, the subsidy would have to be rather large in order to suppress initial investment into coal-fired capacity (without CCS), since it has an important cost advantage over the alternatives.[13]

6. Conclusion

Climate policies will frequently change over the passage of time for many reasons. One important aspect is that there are large uncertainties about the severity of climate change and the cost of technologies needed to mitigate this problem, but as time proceeds, more information about these factors will be obtained either through learning by observation or learning through the conduct of active research. This new knowledge needs to be incorporated in mitigation policies that consequently need to be updated over time. Also, it is a well-known problem that governments find it problematic to stick to long-term plans and–given the global nature of the climate change problem–one should expect countries' willingness to participate in any international climate change mitigation regime to alter over time. As a result, large jumps in e.g. international permit prices are to be expected. Given this, it is important to understand how different

[12] In our analysis, we assume that the switching costs amount to 1% of the capital costs as a crude benchmark.

[13] At the same time, earlier adoption of renewable energy implies that the dependency on fossil fuel supply (here coal) is reduced. For some countries, this can be seen as a substantial step forward in terms of energy security. However, coal is not on the main energy security agenda currently, but other fuels, such as natural gas and oil are, and so additional policies (besides "pure" CO_2 policies) may be warranted, see for example Leiby et al. (1997). However, problems of energy security and risks associated with the supply of fuel inputs are beyond the scope of our analysis and will be left for future research.

forms of policy changes (less frequent and more drastic versus more frequent but less harsh) will influence investment decisions and, therefore, overall costs of providing energy and reducing cumulative CO_2 emissions. We think that our analysis adds new knowledge about these aspects.

We have used a dynamic programming model to analyze the transition dynamics between three typical technologies for electricity generation, whose defining characteristics are their carbon intensities: the first technology is a coal-fired power plant, which can be retrofitted with a CCS module that will capture a fraction of the CO_2 emitted. The third technology is a wind farm, which has high capital costs and a low capacity factor, but which of course outperforms the coal-fired power plant on both fuel costs and CO_2 emissions. In the face of rising CO_2 prices, we see investment into the coal-fired power plant in the beginning of the planning period, gradual phasing in of the CCS technology and finally a transition to wind. Valuing these investment (and also operational) options in one and the same framework enables us to fully capture the interdependence between the individual options. Even though wind might seem a good investment in terms of return when valued individually, the fact that the fictive investor chooses to start out with coal creates an option value of holding on to existing capacity, which puts wind at a disadvantage. At the same time, having the option to update the coal-fired power plant with CCS increases the option value of waiting to install wind in the face of CO_2 price uncertainty.

Furthermore, so as to analyze whether more frequently adapted climate policy (in the form of a fluctuating CO_2 price) is more harmful to both investors and the environment than less frequent but therefore more drastic changes, we have computed the expected value of information both in terms of costs to the power producer and the cumulative CO_2 emission savings. Both indicators confirm that less frequent adaptation of policies should be preferred by investors and policy-makers striving for emissions reductions. In other words, if policies are updated less often, the policy itself will be more efficient in meeting long-term goals as well. Moreover, the longer the time steps between the jumps in the CO_2 price, the less are investors willing to pay for having perfect information. The reason is that the continuous (deterministic) increase in the CO_2 price itself between the jumps is already sufficient to trigger the corresponding investments into less carbon-intensive equipment, which is particularly clear in the subsequent years, just after a jump. As a new stochastic price jump is approached, the number of investments drops due to an increased value of waiting for the succeeding price jump. In general, the difference between investment dates in the stochastic and deterministic cases decreases, as the commitment period length increases. This translates into a smaller expected value of information.

Moreover, the expected value of information when the CO_2 price jumps seldom increases less over rising levels of uncertainty than when there are persistent price fluctuations. This implies that there is an advantage of updating the policy less frequently, if large changes are to be expected in the future course of the CO_2 price. On the other hand, this benefit of price stability has to be valued against the benefit of having flexibility to incorporate new information into climate regimes. We leave this question for future studies.

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References

Azar, C., Rodhe, H., 1997. Targets for stabilization of atmospheric CO_2. Science 276, 1818.
Buchner, B., 2007. Policy uncertainty, investment and commitment periods. IEA information paper COM/ENV/EPOC/IEA/SLT(2007)8, IEA/OECD, Paris.
CAIT, 2007. World Resources Institute's database CAIT. Available at 〈http://cait.wri.org/〉.
Caldeira, K., Jain, A.K., Hoffert, M.I., 2003. Climate sensitivity uncertainty and the need for energy without CO_2 emission. Science 299, 2052–2054.
Cheng, L., Subrahmanian, E., Westerberg, A., 2004. A comparison of optimal control and stochastic programming from a formulation and computation perspective. Computers and Chemical Engineering 29, 149–164.
Dixit, A., Pindyck, R., 1994. Investment under uncertainty. Princeton University Press, Princeton.
EU, European Union, 2005. Council of the European Union, Presidency Conclusions 2005, March 22–23. Available at 〈http://ue.eu.int/ueDocs/cms_Data/docs/pressData/en/ec/84335.pdf〉.
Fleten, S.E., Maribu, K., Wangensteen, I., 2007. Optimal investment strategies in decentralized renewable power generation under uncertainty. Energy 32, 803–815.
Forest, C.E., Stone, P.H., Sokolov, A.P., Allen, M.R., Webster, M.D., 2002. Quantifying uncertainties in climate system properties with the use of recent climate observations. Science 295, 113–117.
Fuss, S., Szolgayova, J., Obersteiner, M., Gusti, M., 2008. Investment under market and climate policy uncertainty. Applied Energy 85, 708–721.
Graßl, H., Kokott, J., Kulessa, M., Luther, J., Nuscheler, F., Sauerborn, R., Schellnhuber, H.J., Schubert, R., Schulze, E.D., 2003. Climate protection strategies for the 21st century: Kyoto and beyond. Report prepared by the German Advisory Council on Global Change (WBGU), Berlin.
Hansen, J., Russel, G., Lacis, A., Fung, I., Rind, D., 1985. Climate response times: dependence on climate sensitivity and ocean mixing. Science 229, 857–859.
Hansen, J., Nazarenko, L., Ruedy, R., Sato, M., Willis, J., Del Genio, A., Koch, D., Lacis, A., Lo, K., Menon, S., Novakov, T., Perlwitz, J., Russell, G., Schmidt, G.A., Tausnev, N., 2005. Earth's energy imbalance: confirmation and implications. Science 308, 1431–1435.
Helm, D., Hepburn, C., Mash, R., 2003. Credible carbon policy. Oxford Review of Economic Policy 19, 438–450.
Hlouskova, J., Kossmeier, S., Obersteiner, M., Schnabl, A., 2005. Real options and the value of generation capacity in the German electricity market. Review of Financial Economics 14, 297–310.
ICC, International Chamber of Commerce, 2007. The world business organisation, Policy statement: Business perspectives on a long-term international framework to address global climate change, Available at 〈www.iccwbo.org〉/uploadedFiles/Long_term_frameworks.pdf.
IEA, International Energy Agency, 2005. Projected costs of generating electricity—2005 update. OECD/IEA, Paris.
IEA, International Energy Agency, 2006. Energy technology perspectives—scenarios and strategies to 2050. OECD/IEA, Paris.
IIASA, International Institute of Applied Systems Analysis, 2007. GGI scenario database. Available at 〈http://www.iiasa.ac.at/Research/GGI/DB/〉.
Laurikka, H., 2007. The impact of climate policy on heat and power capacity investment decisions. In: Antes, R., Hansjürgens, B., Letmathe, P. (Eds.), Emissions Trading and Business, first ed. Physica-Verlag, Wurzburg (Wein).
Laurikka, H., Koljonen, T., 2006. Emissions trading and investment decisions in the power sector—a case study of Finland. Energy Policy 34, 1063–1074.
Leiby, P.N., Jones, D.W., Curlee, T.R., Lee, R., 1997. Oil imports: An assessment of benefits and costs. Oak Ridge National Laboratory November.
Lempert, R.J., Popper, S.W., Resetar, S.A., Hart, S.L., 2002. Capital cycles and the timing of climate change policy. Prepared for the Pew Center on Global Climate Change.
Madlener, R., Kumbaroglu, G., Ediger, V., 2005. Modelling technology adoption as an irreversible investment under uncertainty: The case of the Turkish electricity supply industry. Energy Economics 27, 39–163.
Manne, A.S., Richels, R.G., 1992. Buying Greenhouse Insurance—The Economic Costs of CO_2 Emission Limits. The MIT Press, Cambridge Massachusetts, London, England.
Nordhaus, W.D., Popp, D., 1997. What is the value of scientific knowledge? An application to global warming using the PRICE model. The Energy Journal 18, 1–45.
O'Neill, B.C., Oppenheimer, M., 2002. Dangerous climate impacts and the Kyoto Protocol. Science 296, 1971–1972.
Oppenheimer, M., Petsonk, A., 2005. Article 2 of the UNFCCC: Historical origins, recent interpretations. Climatic Change 73, 195–226.

Peck, S.C., Teisberg, T.J., 1993. Global warming uncertainties and the value of information: An analysis using CETA. Resource and Energy Economics 15, 71–97.

Reedman, L., Graham, P., Coombes, P., 2006. Using a real options approach to model technology adoption under carbon price uncertainty: An application to the Australian electricity generation sector. The Economic Record 82, 64–73.

Reinelt, P.S., Keith, D.W., 2007. Carbon capture retrofits and the cost of regulatory uncertainty. Energy Journal 28, 101–127.

Riahi, K., Grübler, A., Nakicenovic, N., 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. Technological Forecasting and Social Change 47, 887–935.

Roe, G.H., Baker, M.B., 2007. Why is climate sensitivity so unpredictable? Science 318, 629–632.

Stern, N., 2006. The economics of climate change. Cabinet Office—HM Treasury.

Tarui, N., Polasky, S., 2005. Environmental regulation with technology adoption, learning and strategic behavior. Journal of Environmental Economics and Management 50, 447–467.

Tseng, C., Barz, G., 2002. Short-term generation asset valuation: A real options approach. Operations Research 50, 297–310.

UNFCCC, 1992. United Nations Framework Convention on Climate Change. Available at ⟨www.unfccc.org⟩.

Yohe, G., Andronova, N.G., Schlesinger, M.E., 2004. To hedge or not against an uncertain climate future. Science 306, 416–417.

6 The effects of climate policy on the energy–technology mix: an integrated CVaR and real options approach

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1 Introduction

As more evidence about the contribution of anthropogenic GHG emissions to the rate of global warming and the associated damages is brought forward,[1] the debate of whether climate policy should be implemented has shifted towards a different focus. More precisely, the debate centres now around the right policy *instrument* that should be implemented to achieve the desired reduction in emissions before irreversible damages accumulate.

While European countries have introduced a cap and trade system called the European Trading Scheme (ETS), other countries have argued that the resulting CO_2 price will be volatile and therefore detrimental to their industries' profitability. Other suggestions include taxes that could be escalating or constant. If CO_2 prices were deterministic, the height of the threshold, beyond which investment into environmentally friendlier technologies would be triggered, would depend solely on the level of the CO_2 price and its projected rate of growth.

So there are multiple instruments that policy makers can implement to reduce GHG emissions. In this chapter we model such policy as a CO_2 penalty, which could be a tax or a permit price and focus on the effect that volatility of CO_2 prices has on investment at the firm level and how this translates to changes in the aggregate mix of energy technologies. In order to tackle this problem, we first optimize the timing of adopting and operating a technology (e.g. a coal-fired power plant with the flexibility to add a carbon capture module, which can be switched on and off) with a real options model, where both the price of electricity and also CO_2 charges are stochastic. This generates a return distribution, which can then be used as an input to a portfolio model, where the risk measure is the Conditional Value-at-Risk (CVaR). For both volatile and (relatively) stable CO_2 prices, we thus obtain return distributions corresponding to different technologies: fossil-fuel-fired power generation (in the form of a coal-fired power plant) and renewable energy (in the form of an onshore wind farm). Furthermore, we include

biomass-fired generation with carbon capture and storage (CCS) because it is an interesting case, since the biomass that needs to be grown for the combustion process sequesters more CO_2 than is ultimately emitted when using CCS, which leads to negative emissions.

Moreover, facing large uncertainty not only about CO_2 policy as such, but also about many other factors that influence the climate and the energy system, we think that it is important to analyze how the results differ between scenarios, which represent alternative future developments of population and demographics, economic growth and the rate of technological progress. Such scenarios have been developed in IIASA's GGI Database (2007) and provide shadow prices for GHG emissions, which can be used as CO_2 prices in the real options model. We do not only test for changes in investment in the three different scenarios provided in this database, but we also investigate the policy implications of different stabilization targets. More information about these scenarios will be presented when the data used are introduced in Section 3.1.

The results show that the new method of integrating real options with portfolio optimization delivers new insights into investment decision-making under uncertainty. Moreover, the application to climate change policy reveals that return distributions indeed depend on the volatility of the CO_2 price (which remains unspecified and could be a continuously updated tax or the price of a permit) and that such volatility can also work in favor of the policy goals, i.e. make the policy itself more effective.

In this chapter, we will first review the corresponding literature—real options theory, portfolio selection and different risk measures—in order to put our own contribution more into perspective. Then, we will describe the real options model, the data used and the results we obtain. Afterwards, we introduce the CVaR framework and present the results. A discussion of these results and possible policy implications follows. Finally, some extensions for future research are listed.

2 Literature review and contribution

2.1 *Real options theory in electricity planning*

The electricity sector exhibits three special features: 1) the relative irreversibility of investments, since installing new equipment involves large sunk costs, 2) the uncertainty surrounding the investment decisions, and 3) the flexibility of timing investments, so that investment can be postponed or brought forward in time, as new information becomes available. Real options theory provides a framework, in which investment under uncertainty can be investigated when irreversibility and flexibility with respect to the timing of sequential decisions are involved.

Even though options theory had originally been developed for valuing financial options in the 1970s (Black and Scholes, 1973, and Merton, 1973), option pricing was soon discovered to also provide considerable insight into decision-making concerning capital investment. Early frameworks were developed by McDonald and Siegel (1986), Pindyck (1988, 1991, 1993), and Dixit and Pindyck (1994). See Trigeorgis (1996) for a more comprehensive overview. More advanced and with several applications is Schwartz and Trigeorgis (2001).

The basic idea behind using options pricing for investments is that standard net present value calculations do not take into account that there might be a value of waiting in the face of uncertainty about the future evolution of e.g. prices, policies or costs in general. Regarding the opportunity to defer an investment as an option means that we can assign a value to waiting. In other words, investors gain more information about the uncertainty that surrounds economic decisions as time passes by. Therefore, staying flexible by postponing decisions has an option value if the degree of uncertainty is large enough. This value increases if the involved sunk costs are high or if uncertainty increases. In this case it pays off to wait and see how the conditions have changed, especially if they are expected to be rather stable afterwards.

Real options studies, which analyze investment behaviour in the electricity sector are numerous and focus on very different issues: Dixit and Pindyck (1994, pp. 51–54) show in their book how this approach can be useful to support decision-making in electricity planning. Tseng and Barz (2002), Hlouskova et al. (2005) and Deng and Oren (2003) amongst many others have analyzed the effects of e.g. variability in loads and the inclusion of specific operational constraints on investment. Recently, interest has shifted more to long-term planning again. Fleten et al. (2007) show that investment in power plants relying on renewable energy sources will be postponed beyond the traditional net present value break even point when a real options approach with stochastic electricity prices is used. Madlener et al. (2005) develop a dynamic technology adoption model to incorporate multiple technologies in a kind of vintage setting, but they explicitly borrow elements from real options theory as well. A recent article by Reinelt and Keith (2007) focuses on retrofitting existing fossil-fuel-fired capacity with CCS, which makes it similar to our framework.

A selection of some other interesting applications concern research financing, electricity trading and the importance of market structure. Davis and Owens (2003) optimize the amount of renewable energy R&D by valuing the potential savings from developing renewable energy in the face of fluctuating fossil fuel prices. Chaton and Doucet (2003) incorporate the trade of electricity and consider also demand and fuel price uncertainty, load duration curves and equipment availability. Keppo and Lu (2003) investigate how a large electricity producer forms his/her decision to produce some planned quantity of power and how this can affect the market price of electricity.

While investment optimization in a power plant or an incremental investment such as CCS is performed by the individual producer, large investors

will typically want to invest in a technology *portfolio* rather than concentrate on a single technology or chain of technologies (e.g. coal plus CCS). Our contribution is to combine portfolio optimization with the results derived from our real options framework. In particular, we use the real options model to find the optimal investment strategy and its implied return distributions, which can then be employed as an input into the portfolio optimization. The next section therefore places our approach within the existing literature of portfolio optimization.

Portfolio theory and applications to energy investments

Inasmuch as the origins of real options theory are rooted in finance, the same is true for portfolio theory pioneered by Nobel laureate Markowitz (1952) and further developed by Merton (1969), Samuelson (1969) and Fama (1970). The theory starts out from the observation that most investors are risk averse, i.e. they refrain to a certain extent to buy assets that exhibit a large variance in their returns. To quote Markowitz himself, "[. . .] the investor does (or should) consider expected return a desirable thing and variance of return an undesirable thing," (Markowitz, 1952, p. 77). Investors thus compose their portfolios of assets that exhibit lower expected rates of return, but which are relatively secure, and of assets that have a high expected rate of return, for which they have to accept a higher level of variance. It is the tradeoff between expected return and variance that matters for the investor and leads to a diversification of the portfolio. The main result concerning this tradeoff is that investors should select portfolios that maximize expected returns given a pre-specified level of variance or minimize variance given a desired level of return or more.[2]

Later on, financial portfolio theory was adapted and applied to real assets as well. Examples include the valuation of offshore oil leases (Helfat, 1988) and the valuation of financing long-term projects. Applications involving energy planning date back as far as 1976 (Bar-Lev and Katz, 1976). Lately, interest in the topic has arisen again, see for example Awerbuch and Berger (2003), Awerbuch (2006) and Roques et al. (2006).

The study that is most closely related to ours is by Roques et al. (2006), who apply a mean-variance framework to UK diversification in electricity sector investment, where they include the risks associated with carbon price fluctuations and electricity price volatility beyond fuel price uncertainty that other authors have mainly been focusing on. Instead of optimizing at the firm level by using a real options model as we do, however, their return distributions are generated by net present value Monte Carlo simulations for three scenarios. The first scenario has independent, stochastic price processes, while the second scenario also takes into account that the price processes might be correlated. The third scenario has a fixed electricity price in order to assess the impact of long-term purchase contracts. In terms of their conclusions, it remains questionable whether the market can provide incentives to investors to opt for a socially optimal fuel mix. At the same time, it becomes apparent that the correlations between the price processes influence the results significantly.

Although the mean-variance (MV) approach by Markowitz (1952) explains diversification and the risk-return tradeoff in a very straightforward way, it has the disadvantage that it maximizes only quadratic utility, i.e. it is not a valid method to tackle problems involving preferenees for higher-order return moments. As an example, return distributions might be skewed and have fat tails, which would imply higher losses beyond a certain threshold.[3] In fact, previous analysis has shown that—under carbon price and electricity price uncertainty—power plant return distributions are not necessarily normal (see Fortin et al. (2007)) and therefore the variance is not an appropriate measure of risk, which makes alternative measures such as the Conditional Value-at-Risk (CVaR) interesting (see also Rockafellar and Uryasev, 2000). In this chapter we use the CVaR as the risk measure and not the variance. The next section reviews the corresponding literature in more detail.

2.3 Mean-Variance vs (Conditional) Value-at-Risk

Even though MV portfolios are still used for risk management in financial institutions, some have started to employ other measures of risk, which capture extreme events providing information on the tail of a distribution. Two candidate risk measures are the Conditional Value at Risk (CVaR) and the Value at Risk (VaR), where the former is closely related to the latter and offers additional desirable properties. In order to explain the difference between the two measures, let us first define them carefully. The β-VaR of a portfolio is the lowest amount α such that, with probability β, the portfolio loss will not exceed α, whereas the β-CVaR is the conditional expectation of losses above that amount α, where β is a specified probability level.[4] This is illustrated in Figure 6.1, where it can clearly be seen that the β-VaR corresponds to the β-percentile of the distribution, whereas the β-CVaR is the mean of the random values exceeding VaR.

The shortcomings of VaR compared with CVaR relate to its usefulness in risk management and its technical properties. Losses exceeding the threshold value are not taken into account by VaR, but they are by CVaR. Moreover, VaR is only a coherent risk measure in the sense of Artzner et al. (1999), if distributions can safely be assumed to be normal. In contrast, CVaR is always a coherent risk measure, which is thus useful for a broader range of applications including those involving non-normal distributions. Furthermore, the results in Rockafellar and Uryasev (2000, 2002) make computational optimization of CVaR readily applicable. Note that, under certain conditions, the minimization of VaR and CVaR and the MV framework yield the same optimal portfolio allocations provided that the underlying distributions are normal.[5] This does not apply if the assumption of normality

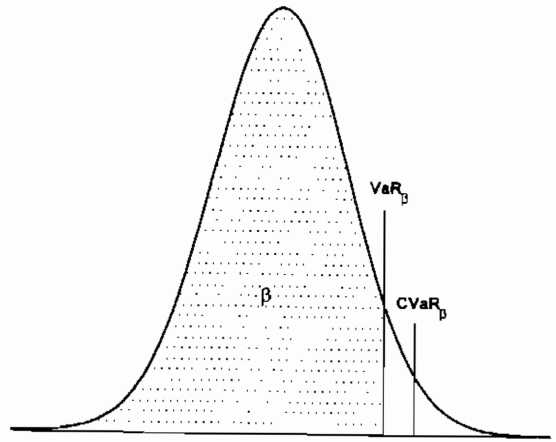

Figure 6.1 Illustration of β-VaR and β-CVaR for a normal loss distribution.

is violated. Fortin et al. (2007) have shown that, for the model that we also use here, the data and the parameter setting, "both the univariate distributions and the joint distribution (copula) of the returns, which are the results from the real options procedure, do not seem to be normal." As far as we know, combining real options with portfolio optimization using CVaR is a new approach and the application to climate change policy analysis is original as well. Recent literature that has undertaken steps into similar directions includes Doege et al. (2006), Fichtner et al. (2002), Spangardt et al. (2006), and Unger and Lüthi (2002).

In contrast to Fortin et al. (2007), who compare results for different levels of the CO_2 price, our focus is more on the impact of CO_2 price *volatility* on the composition of the generating portfolio. In addition, we want to see what the optimal portfolios are in scenarios that are based on different predictions about population growth, trade and technology proliferation, urbanization, migration, etc. For this purpose we make use of the GGI scenarios (IIASA, 2007), which will be described in more detail in the following section. Even though the results obtained are very intuitive, the numerical results for the individual technologies are supposed to be rather illustrative. The deeper purpose of this chapter is to illustrate the usefulness of this new approach for analyzing the impact of climate change policy and the associated uncertainty in different scenarios on the aggregate energy technology mix—and not to give ad hoc investment advice.

3 A real options framework for investment in power generation equipment

3.1 Model setup and technology data

This model is intended to determine the optimal investment plan for a profit-maximizing electricity producer (or planner), who has to produce a specific amount of electricity but faces stochastic CO_2 and electricity prices.

In this chapter we consider a coal-fired and a biomass-fired power plant and a wind farm. The same real options framework is used to value options to invest into them.[6] For the coal-fired and the biomass-fired power plants there is, in addition, the possibility to retrofit with CCS and to switch it on or off when the CO_2 price fluctuates widely. Thereby we generate return distributions for our CVaR model. The investor's decision problem is to maximize expected profits under uncertainty about future electricity and CO_2 prices. CO_2 prices, P^c_t, and electricity prices, P^e_t, are modelled as stochastic processes:

$$\ln P^c_t - \ln P^c_{t-1} = c + \varepsilon^c_t,$$

$$\ln P^e_t = c_1 + c_2 \cdot \ln P^e_{t-1} + \varepsilon^e_t$$

where $\varepsilon^c_t \sim N(0,(\sigma^c)^2)$ and $\varepsilon^e_t \sim N(0,(\sigma^e)^2)$, and the two disturbances are correlated with ρ as explained earlier.

So we can formulate the investor's decision problem as follows: x_t is the state variable describing whether the basic plant, the CCS module, or both have been built and whether the CCS module is currently running. Let a_t denote the action, i.e. the control variable. Possible actions are 1) building the power plant without the CCS module, 2) building the power plant with CCS module, 3) adding the CCS module, 4) switching the CCS module off, 5) switching the CCS module on, and 6) doing nothing. $A(x_t)$ is the set of feasible actions. As a constraint, only feasible actions $a_t \in A(x_t)$ can be performed. The investor faces the following problem:

$$\max_{\{a_t\}_{t=0}^{T}} \sum_{t=0}^{T} \frac{1}{(1+\gamma)^t} \cdot E[\pi(x_t, a_t, P^c_t, P^e_t)]$$

where starting values are known and γ is the discount rate (later set to … percent). The profit $\pi(\cdot)$ is income from electricity and heat production minus the cost of fuel, CO_2 expenses, operational and maintenance (O&M) costs and costs associated with a potential action, $c(a_t)$. We assume that the installed plant will produce continuously, thereby producing a fixed amount of output for a fixed amount of input each year.[7] The profit is:

$$\pi(x_t, a_t, P^c_t, P^e_t) = q^e(x_t) \cdot P^e_t + q^h(x_t) \cdot P^h - q^f(x_t) \cdot P^f_t - q^c(x_t) \cdot P^c_t - OC(x_t) - c(a_t)$$

P^h is the heat price, P^f is the fuel price (which is zero for wind), OC is O&M cost per year, and q^e, q^h, q^c, and q^f are the annual quantities of electricity, heat (which is zero for wind), CO_2 and fuel, respectively. We assume that installing a power plant implies its immediate use, but adding construction times does not change our qualitative results, if they do not differ immensely from each other.

The Bellman equation corresponding to the profit maximization in (6.3) is:

$$V_t(x_t, P^c_t, P^e_t) = \max_{a_t \in A(x_t)} \{\pi(a_t, x_t, P^e_t, P^c_t) + \frac{1}{(1+\gamma)^t} \cdot E[V_{t+1}(x_{t+1}, P^e_{t+1}, P^c_{t+1} | x_t, P^e_t, P^c_t)]\} \qquad (6.4)$$

with $V_t(\cdot)$ as the value function and $T = 50$ as the planning horizon. This problem can be solved recursively with dynamic programming techniques, and $E[V_t(x_{t+1}, P^e_{t+1}, P^c_{t+1} | x_t, P^e_t, P^c_t)]$ can be calculated either by means of finite difference equations, binomial lattices, or by Monte Carlo simulation. We use the latter (with 10,000 simulations) because it can easily be adapted when the framework is extended. Moreover, it remains computationally efficient for a high degree of complexity.

The solution of the recursive optimization part is a multidimensional matrix containing the optimal action a_t for every time period, state and price. We refer to these optimum actions as "strategies." In order to analyze the outcome, we simulate possible CO_2 and electricity price paths and the corresponding decisions from the output. By plotting the distribution of the optimal investment timing for all the different price paths, we get the final results.

Once we have thus derived the optimal decisions a_t, total discounted profits and total discounted costs can be computed for realized outcomes and divided by each other to obtain the return (distribution), which is then an input to the portfolio optimization in Section 4.

Concerning the data, electricity prices are estimated from spot market data of the European Energy Exchange. The CO_2 prices are based on the projections for GHG shadow prices taken from IIASA's GGI Scenario Database where we consider three scenarios and both low and high stabilization for each one of them. The data used can be found in the Appendix, but we want to describe the scenarios briefly here to facilitate understanding and interpretation of the results subsequently.

The first scenario is the so-called "B1" scenario, which assumes a very optimistic outlook on future development: population peaks and starts to decline after mid-century; there is much progress, which results in clean and resource efficient technologies, economies make a transition to service and information economies, and policies are geared towards social, economic and environmental sustainability. It can actually be observed that GHG prices then even decrease towards the end of the projection period. In contrast, scenario "A2r" draws a much more pessimistic picture for the future, where fertilities do not converge in the near term and population increases substantially. Furthermore, economic development is very concentrated in specific regions and technological progress is slow and fragmented. Evidently, stabilization is not achieved easily and it turns out that a low stabilization target is not even feasible.

Finally, the third scenario, "B2", is a kind of "intermediary" scenario in the sense that technological change, population growth, economic development, etc. all lie in between the assumptions of B1 and A2r.[8]

Parameter estimates for the electricity price process as specified in Equation (6.1) are $c_1 = 1.655$, $c_2 = 0.541$, and $\sigma^e = 0.092$. For the CO_2 price process, c varies from scenario to scenario, but in general (with different starting values of the CO_2 price) the rate of increase is around 5 percent, and σ^c is tested for both a low value (1 percent) and a high value (10 percent) for the purpose of sensitivity analysis and because there is much uncertainty about future rates of volatility, which is the motivation of this exercise in the first place. The two noise processes are correlated with $\rho = 0.7$, which is an admittedly arbitrary choice, but where lower and higher values do not change the optimal actions, i.e. the results are robust across different values of the correlation parameter. Coal prices are assumed to remain constant throughout the planning horizon, which is reasonable for many countries looking at data acquired by the IEA (2005).[9] Another justification might be to assume that the producer engages in long term supply contracts for coal.

Technical data and costs for all technologies can be found in Table 6.1. These technologies are representative of fossil-fuel-based technologies (coal), less carbon-intensive technologies (biomass) and zero-emission renewables (wind). As the electricity output of the three plants (without CCS[10]) is the same, they are similar in size. We have conducted this "normalization" for the sake of comparability of the individual plants.

Table 6.1 Power plant data for coal, wind and biomass

Parameters	*Coal*	*Coal + CCS*	*Wind*	*Bio*	*Bio + CCS*
Technical features					
Electricity output [TWh/yr]	3,285	2,642	3,285	3,285	2,628
CO_2 emissions [kt CO_2/yr]	2,155	292	0	0	−2,691
Fuel consumption [TJ/yr]	23,188	23,188	0	29,565	29,565
Fuel cost [€/TJ]	1,970	1,970	0	1,692	1,692
O&M fixed cost [1,000 €/yr]	40,250	48,450	19,667	77,000	91,568
Installed capacity [MW]	500	402	1,389	500	400
Power efficiency [%]	46	37	27	40	32
Heat efficiency [%]	34	34	0	16	16
Heat price [€/TJ]	11,347	11,347	n/a	11,347	11,347
Capital costs					
Common parts [1,000 €]	686,500	686,500	n/a	402,029	402,029
Cost CCS module [1,000 €]		137,946			320,333
Total capital cost [1,000 €]	686,500	824,446	1,042,735	402,029	722,362

IEA/OECD (2005).

The high O&M costs of the biomass plant are due to the relative immaturity of the technology. Therefore, we allow for slight rates of technical change (3 percent), which lead these costs to drop until they eventually reach about the same magnitude as coal, which is technically very similar in O&M. Another peculiarity of the biomass plant is the zero (without CCS) and negative (with CCS) amount of emissions (see Table 6.1). This can be explained by the fact that biomass-based electricity production requires that additional biomass is grown, which will extract more CO_2 from the atmosphere, and we assume this to be subsidized or rewarded by extra CO_2 allowances. We assume that the amount of CO_2 emissions for a biomass plant without CCS technology is equal to this support.[11]

3.2 *Results from the real options approach*

The results from valuing the above-mentioned investment and operational options are the return distributions that we will need for our portfolio optimization in the next section. Tables 6.2 and 6.3 report the relevant statistics of our return distributions for a strict and a less strict stabilization target respectively. The -VaR and -CVaR are computed for a confidence level of 95 percent and 99 percent respectively. More detailed explanations on CVaR as a risk measure can be found in Section 4.

Note also that for presentation purposes we have chosen to report -CVaR and -VaR, that is, instead of using losses, we refer to returns. -VaR of portfolio x at the significance level β is thus the minimum portfolio return "guaranteed" with probability β and -CVaR of portfolio x is the conditional expectation of portfolio returns given they are smaller than -VaR(x). Furthermore, -CVaR(x) ≤ -VaR(x). The portfolio's risk is increasing when -CVaR is decreasing.

Let us start with the "middle" scenario as a benchmark. In B2, for the strict stabilization target, we see that -CVaR is larger in the low-volatility cases, which makes intuitive sense: like in an MV framework, more volatility leads to higher risk for all technologies, except for wind, which stays largely unaffected.

The neutrality of wind can be explained by the fact that it is not directly affected by CO_2 prices in the first place. If we see slight changes in other scenarios, these are due to the correlation of the noises of the electricity and CO_2 prices. Since electricity prices also affect wind returns, a marginal adjustment to the distribution also happens for wind, but most of the time these effects do not show up in the first three digits after the decimal point.

Another observation in the 480 ppm case in B2 is that expected returns are higher when volatility is large. This implies that for higher returns the investor needs to accept a higher risk in terms of -CVaR and lower risk can only be achieved at the expense of lower returns. These outcomes thus evidently

Table 6.2 Descriptive statistics of return distributions of coal fired and biomass-fired power plants and of onshore wind mills for 95 percent confidence

	CO_2 price volatility	*Mean return*	*-CVaR*	*-VaR*
B1, 480 ppm				
Coal	high	1.770	1.686	1.719
Coal	low	1.755	1.726	1.714
Biomass	high	1.806	1.562	1.581
Biomass	low	1.794	1.728	1.712
Wind	high	1.815	1.727	1.705
Wind	low	1.815	1.727	1.705
B1, 670 ppm				
Coal	high	1.730	1.713	1.719
Coal	low	1.775	1.726	1.714
Biomass	high	1.644	1.594	1.581
Biomass	low	1.644	1.594	1.581
Wind	high	1.815	1.690	1.673
Wind	low	1.815	1.690	1.673
B2, 480 ppm				
Coal	high	1.508	1.449	1.435
Coal	low	1.499	1.462	1.453
Biomass	high	1.723	1.587	1.572
Biomass	low	1.644	1.648	1.634
Wind	high	1.815	1.727	1.705
Wind	low	1.815	1.727	1.705
B2, 670 ppm				
Coal	high	1.724	1.726	1.714
Coal	low	1.724	1.687	1.677
Biomass	high	1.644	1.594	1.581
Biomass	low	1.644	1.594	1.581
Wind	high	1.815	1.727	1.705
Wind	low	1.815	1.727	1.705
A2r, 670 ppm				
Coal	high	1.643	1.593	1.579
Coal	low	1.638	1.597	1.587
Biomass	high	1.650	1.592	1.580
Biomass	low	1.642	1.594	1.581
Wind	high	1.815	1.727	1.705
Wind	low	1.815	1.727	1.705
A2r, 820 ppm				
Coal	high	1.778	1.732	1.721
Coal	low	1.778	1.729	1.717
Biomass	high	1.644	1.594	1.581
Biomass	low	1.644	1.594	1.581
Wind	high	1.815	1.690	1.673
Wind	low	1.815	1.709	1.673

Results for scenarios B1, B2 and A2r with high and low CO_2 price volatility. Note that A2r is a scenario where stabilization at 480 ppm is not even possible, we compare 680 and 820 ppm instead.

Table 6.3 Descriptive statistics of return distributions for coal-fired and biomass-fired power plants and of onshore wind mills for 99 percent confidence

	CO_2 price volatility	*mean return*	*-CVaR*	*-VaR*
B1, 480 ppm				
Coal	high	1.770	1.666	1.633
Coal	low	1.755	1.706	1.697
Biomass	high	1.806	1.573	1.549
Biomass	low	1.794	1.701	1.689
Wind	high	1.815	1.705	1.673
Wind	low	1.815	1.705	1.673
B1, 670 ppm				
Coal	high	1.774	1.713	1.719
Coal	low	1.775	1.706	1.697
Biomass	high	1.644	1.572	1.562
Biomass	low	1.644	1.572	1.562
Wind	high	1.815	1.690	1.673
Wind	low	1.815	1.690	1.673
B2, 480 ppm				
Coal	high	1.508	1.426	1.414
Coal	low	1.499	1.470	1.440
Biomass	high	1.723	1.563	1.552
Biomass	low	1.644	1.604	1.612
Wind	high	1.815	1.690	1.673
Wind	low	1.815	1.690	1.673
B2, 670 ppm				
Coal	high	1.724	1.706	1.697
Coal	low	1.724	1.671	1.663
Biomass	high	1.644	1.572	1.562
Biomass	low	1.644	1.572	1.562
Wind	high	1.815	1.690	1.673
Wind	low	1.815	1.690	1.673
A2r, 670 ppm				
Coal	high	1.643	1.569	1.559
Coal	low	1.638	1.580	1.572
Biomass	high	1.650	1.571	1.562
Biomass	low	1.642	1.572	1.562
Wind	high	1.815	1.690	1.673
Wind	low	1.815	1.690	1.673
A2r, 820 ppm				
Coal	high	1.778	1.714	1.705
Coal	low	1.778	1.709	1.717
Biomass	high	1.644	1.572	1.562
Biomass	low	1.644	1.572	1.562
Wind	high	1.815	1.690	1.673
Wind	low	1.815	1.709	1.673

Results for scenarios B1, B2 and A2r with high and low CO_2 price volatility. Note that A2r is a scenario where stabilization at 480 ppm is not even possible, we compare 680 and 820 ppm instead.

warrant a portfolio optimization approach, which will be implemented in the following section.

Moreover, all scenarios show that expected return remains stable or decreases, while risk increases, as the confidence level β grows. This is because as β rises, a larger part of the right tail of the distribution (namely $100 \cdot \beta$ percent) is captured and the conditional expected return from the smaller left tail ($100(1-\beta)$ percent) is maximized, which can also be seen in Figures 6.2 and 6.3 later in this section.

When we turn to other scenarios, however, we do not always see the same clear relationship between risk and volatility. In fact, the following explanations will demonstrate that this is because -CVaR is a risk measure providing much richer information about returns. In scenario B1 for the strict stabilization target, coal becomes *more risky* when volatility *decreases* for $\beta = 95\%$ and less risky when $\beta = 99\%$, while biomass becomes less risky in both cases. It might seem counter-intuitive that coal should get more risky when volatility is lower, but a look at the change in the return distributions in Figure 6.2 explains this observation: because the tail of the low volatility distribution is flatter at the 99 percent threshold than that of the high volatility distribution, the area to the left of the threshold is smaller and so is (CVaR) risk therefore. However, since the low volatility distribution is much more compact, the rise from 99 percent to 95 percent is much steeper than that of the high volatility distribution and the area left of 95 percent larger as a consequence. Note that the variance increases as intuition and theory suggest, so in an MV framework coal would always be more attractive in the low volatility situation. With CVaR, we can be more specific about the desired confidence level (and

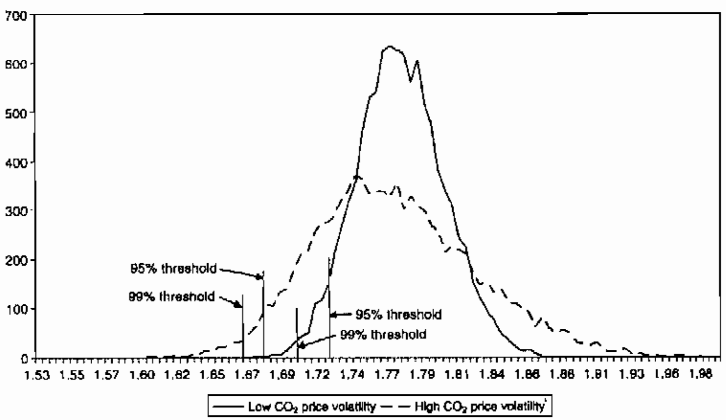

Figure 6.2 Coal return distributions for high and low volatility cases.

Note: The scenario is B1; stabilization target is 48 ppm.

analyze its implications); and it is possible to capture information about the tail of the distributions as well.

For biomass, the high volatility distribution is not only wider than the low volatility distribution, but it is also more skewed, as can be seen in Figure 6.3. This is the reason why more volatility also always leads to more risk in terms of -CVaR for biomass in Tables 6.2 and 6.3. The reason behind the change in the shape of the distribution is that, with larger CO_2 price fluctuations, investment into the CCS module is triggered less often[12] and the investment dates are more spread out over time. However, the CCS module increases the returns from biomass substantially due to the credits received from "negative" emissions and with more cases without CCS there is also a higher frequency of low return outcomes.[13] In the case of coal the CCS module is always installed (though the investment date also spreads out as volatility increases), since CO_2 costs have to be equally borne in both high and low volatility situations, while biomass has zero emissions without CCS (because the growing of fuel biomass sequesters as much CO_2 as the combustion of biomass produces).

With a less strict target in both B1 and B2, the CCS module is never built for biomass and only sporadically for coal. As can be verified in Tables 6.2 and 6.3, both the -VaR and the -CVaR remain unchanged in these cases (because with zero emissions biomass is only marginally affected by σ^c via the correlation between the noises of the price processes). Moreover, less strict targets lead to higher coal returns and lower or stable biomass and wind returns for

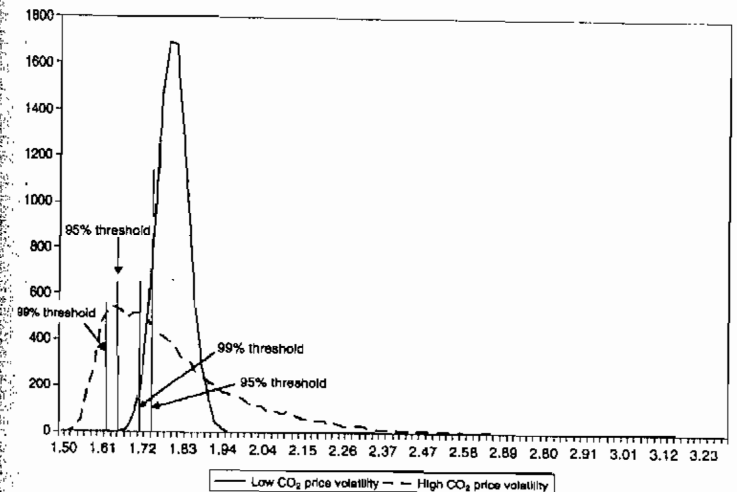

Figure 6.3 Biomass return distribution for high and low volatility cases.

Note: The scenario is B1; stabilization target is 480 ppm.

the obvious reason that CO_2 prices will be at lower levels, while risk generally declines.

The highest expected return is that of wind, followed closely by biomass in B1, 480 ppm with high volatility. The reason for wind displaying such high expected returns is that, in addition to the zero fuel costs, the wind farm owner does not face any extra costs in terms of CO_2 emissions. And since we observe the returns and not the profits, wind appears to be an attractive investment option in terms of expected return. Coal is the least risky technology in all scenarios when the less strict stabilization target applies. In B1, for the stricter target, wind outperforms coal in terms of risk when $\beta = 99\%$ and in B2, 480 ppm, coal is even more risky than biomass. This is also the case in the low stabilization target case in A2r. Remember that A2r is a pessimistic scenario, in which large CO_2 prices are needed to stabilize at a relatively low target, so coal is especially disadvantaged here. Let us now turn to the second part of this analysis—the portfolio optimization.

4 The CVaR model for the aggregate technology mix

4.1 The applied framework

Value-at-risk (VaR) is closely related to CVaR and still the more widely used risk measure as well. However, as briefly mentioned in Section 3, VaR has several disadvantages, discussed in e.g. Rockafellar and Uryasev (2000) and Krokhmal et al. (2001). Therefore, the number of CVaR applications has been growing quickly over the last years. Examples are in the area of energy risk management (Doege et al., 2006), crop insurance (Schnitkey et al., 2004 and Liu et al., 2006), power portfolio optimization (Unger and Lüthi, 2002), hedge funds applications (Krokhmal. et al., 2005), pension funds management (Bogentoft et al., 2001), and multi-currency asset allocations (Topaloglou et al., 2003).[14]

CVaR may be considered as an extension of VaR, as it provides a sort of approximation of VaR because it can be interpreted as an upper bound of VaR (see also Section 2.3). Minimizing CVaR instead of VaR in portfolio optimization might thus be seen as a more "conservative" approach. Moreover, CVaR makes more information available to the decision maker than VaR, since VaR denotes the maximum losses that an investor faces subject to some pre-specified probability (which corresponds to the most probable situation), while CVaR also provides information about the size of the potential losses in the case of the less probable event. In addition, CVaR is relatively easy to compute because the calculation can be reduced to a linear programming problem, which can effectively be solved using standard applied software available on the market. As Fortin et al. (2007) have shown, the assumption of normality cannot be defended for return distributions with the parameters that we also use here, so the application of CVaR will yield results different from the traditional MV optimization.

Defining CVaR according to Rockafellar and Uryasev (2000), let $f(x,y)$ be the loss function depending on the investment strategy $x \in \mathbf{R}^n$ and the random vector $y \in \mathbf{R}^m$, and let $p(y)$ be the density of y. The probability of $f(x,y)$ not exceeding some fixed threshold level α is:

$$\psi(x, \alpha) = \int_{f(x,y) \le \alpha} p(y)dy.$$

The β-VaR is defined by:

$$VaR_\beta(x) = \alpha_\beta(x) = \min\{\alpha | \psi(x, \alpha) \ge \beta\},$$

implying that, with probability β, losses will not exceed the threshold level $\alpha_\beta(x)$ for a given investment strategy x. The β-CVaR is finally defined by:

$$CVaR_\beta(x) = \varphi_\beta(x) = (1-\beta)^{-1} \int_{f(x,y) \ge \alpha_\beta(x)} f(x,y)\, p(y)dy,$$

which is the expected loss given that the loss exceeds the β-VaR level, hence conditional expected loss, or conditional VaR, where the risk measure depends explicitly on the confidence level β. When clear from the context, we will drop β and x.

Looking back at Figure 6.1, the difference between VaR and CVaR as a risk measure becomes even clearer now: the β-VaR is the boundary of the shaded area of size β. The expected value of the losses beyond that boundary is the conditional value that is at risk. In other words, VaR is the threshold of the losses that will not be exceeded with the fixed probability β, it just refers to what is known with the probability β (called also confidence level). VaR does of course not convey any information about the magnitude of the losses that could be incurred beyond the confidence level. Let us assume we are interested in the assessment of some random value (possible loss) and we know with, say, 99 percent confidence the upper threshold (VaR). Knowing that information does not imply that we have any idea about what can be expected in case the threshold is exceeded, which will happen in 1 percent of the cases. Of course, this information may be extremely important for decision-making. The CVaR, as the expectation of the random value (in case it is exceeding the threshold -VaR), does take this into account, and thus contains additional useful knowledge. In this sense, CVaR outperforms VaR especially when the tail is "fat".

Both VaR and CVaR are applicable to returns as well as to losses, because one may consider returns as negative losses (and vice versa). In the following, losses are defined as negative returns and thus we will report -VaR and -CVaR to indicate respectively the lower threshold for returns and expected returns in case they are lower than that threshold.

Let us consider n different technology chains that can be invested into. (In our application, for example, the first "chain" is a coal-fired power plant plus CCS, then we have a biomass-fired plant plus CCS as the second one and wind power as a single technology). Values y^i, $i = 1, \ldots, n$ reflect the *return on investment* (ROI) for each technology chain. We assume the vector $y = [y^1, \ldots, y^n]^T \in \mathbf{R}^n$ of ROIs to be a random vector having some distribution and describe the investment strategy using the vector $x = [x^1, \ldots, x^n]^T \in \mathbf{R}^n$ where the scalar value x^i, $i = 1, \ldots, n$ reflects the fraction of capital invested into technology i. The return function depends on the chosen investment strategy and the actual ROIs; computed as $x^T y$. As the actual ROI is unknown, there is a specific degree of risk associated with investment strategy x. To measure this risk and find the corresponding optimal x, our optimization is based on minimizing CVaR with a loss function $f(x,y)$ (i.e. negative returns):[15]

$$f(x, y) = -x^T y.$$

Following Rockafellar and Uryasev (2000) and Krokhmal et al. (2001), we approximate the problem of minimizing CVaR by solving a piece-wise linear programming problem and reduce this to a *linear programming* (LP) problem with auxiliary variables. For both cases, a sample $\{y_k\}_{k=1}^{q}$, $y_k \in \mathbf{R}^n$ of the ROI distribution is used to construct the LP problem. Concerning the investment strategy in the sense that it should deliver a specified minimum expected return (or limited expected loss), the LP problem is equivalent to finding the investment strategy minimizing risk in terms of CVaR:

$$\min_{(x,\alpha,u)} \alpha + \frac{1}{q(1-\beta)} \sum_{k=1}^{q} u_k$$

$$s.t.\ e^T x = 1,\ m^T x \geq R,\ x \geq 0,\ u \geq 0,\ y_k^T x + \alpha + u_k \geq 0,\ k = 1, \ldots, q \qquad (6.5)$$

where $u = [u^1, \ldots, u^q]^T$, $u^k \in \mathbf{R}$, $k = 1, \ldots, q$ are auxiliary variables, $e \in \mathbf{R}^n$ is a vector of ones, q is the sample size, $m \in \mathbf{R}^n$ is the expectation of the ROI vector y, i.e. $m = E(y)$, R is the minimum expected portfolio return, α is a threshold of the loss function (and therefore also the upper bound of VaR) and β is a confidence level. (x_*, α_*) of the solution of equation (6.5) yields the optimal x_*, so that the corresponding β-CVaR reaches its minimum.[16]

In summary, we minimize CVaR-risk subject to a given expected return. In the experiments we conduct, we employ values for this required expected return R that are in fact not binding because we only want to study the impact of uncertainty and investment patterns across different scenarios to derive policy implications. Setting R high would exclude technologies that could have been interesting alternatives from the point of view of their risk profiles and we want to avoid this in our analysis. In the next section we present the results of computing VaR and CVaR for different levels of confidence β and different degrees of uncertainty σ^c across the scenarios described earlier.

4.2 Final results

In Table 6.4 we present the results from the portfolio optimization. Note that we are having a relatively low constraint on expected portfolio returns, R, so that it is indeed not binding.[17] Fortin et al. (2007) also investigate the effect of having different binding return constraints, but we want to focus on the composition, return and risk level of portfolios under different levels of CO_2 price volatility and in the different scenarios described above.

In addition, the maximum percentage that biomass and wind can attain in the complete portfolio is constrained to 20 percent each. The choice to introduce an "artificial" maximum capacity constraint is motivated by the fact that 100 percent wind and biomass portfolios are not feasible, even if desirable, for most countries owing to a lack of locations for efficient wind farms and lack of space to grow enough fuel for biomass-fired power generation. While we do not know if this 20 percent constraint is too small or too big as compared to reality, we think that it serves our illustrations quite well. Furthermore that some countries might even be able to adopt higher portions of these renewables.

In terms of the results, we can generally confirm from the numbers in Table 6.4 that there is diversification as we go from low to high volatility cases, at least in the scenarios with ambitious stabilization targets. When these targets are less stringent, we either see portfolios that are composed of 80 percent coal and 20 percent wind (in B2) or portfolios that are completely coal-dominated (in B1 and A2r). This is of course due to low CO_2 prices and portfolio returns are indeed highest and (CVaR) risks lowest for these cases. Note also that increases in β lead to higher *portfolio* (CVaR) risk in the same way as the individual CVaRs in the previous section. Intuitively, increasing the confidence level and thus decreasing the incidence of risk, the risk in terms of expected losses in the unfavorable case (CVaR) increases. By definition, the risk in terms of CVaR for single asset portfolios (with 100 percent coal, biomass or wind) increases with increasing confidence level β. So it not surprising that also the optimal portfolio risk increases with growing confidence level, which is exactly what the results show.

Let us now compare between scenarios in order to get an overview of the results of our analysis. As the lowest feasible stabilization target in A2r is 670 ppm, we choose this as our basis for comparison with B1 and B2. B1 portfolios have the highest expected return, followed by those of B2. The lowest return is that of A2r because the CO_2 price needed to stabilize at such a low target in such a scenario, where all factors make it difficult to save or even cut emissions, is much higher than in the other two cases. As a consequence, expected returns are much more vulnerable to fluctuations in CO_2 prices and the A2r portfolios also fare worst in terms of (CVaR) risk. B2 is less risky and B1 safest, according to the results in Table 6.4.

This seems to imply that investors and producers will suffer from lower returns and more risk, especially if they have such poor prospects as in the

Table 6.4 Optimal portfolio in terms of minimal risk for different levels of CO_2 price volatility and confidence levels

	$\beta = 95\%$, high σ^c	$\beta = 95\%$, low σ^c	$\beta = 99\%$, high σ^c	$\beta = 99\%$, low σ^c
B1, 480 ppm				
Coal	68.5	60.0	68.7	80.0
Biomass	11.5	20.0	11.3	0.0
Wind	20.0	20.0	20.0	20.0
R_e	1.783	1.775	1.783	1.763
-VaR	1.729	1.721	1.709	1.702
-CVaR	1.717	1.708	1.698	1.693
B1, 670 ppm				
Coal	100.0	100.0	100.0	100.0
Biomass	0.0	0.0	0.0	0.0
Wind	0.0	0.0	0.0	0.0
R_e	1.740	1.775	1.774	1.775
-VaR	1.730	1.726	1.713	1.706
-CVaR	1.719	1.714	1.703	1.697
B2, 480 ppm				
Coal	60.0	60.0	60.0	80.0
Biomass	20.0	20.0	20.0	0.0
Wind	20.0	20.0	20.0	20.0
R_e	1.612	1.604	1.612	1.604
-VaR	1.564	1.553	1.547	1.533
-CVaR	1.553	1.541	1.538	1.522
B2, 670 ppm				
Coal	80.0	80.0	80.0	80.0
Biomass	0.0	0.0	0.0	0.0
Wind	20.0	20.0	20.0	20.0
R_e	1.742	1.742	1.742	1.742
-VaR	1.699	1.688	1.682	1.667
-CVaR	1.689	1.675	1.673	1.656
A2r, 670 ppm				
Coal	64.1	80.0	64.9	80.0
Biomass	15.9	0.0	15.1	0.0
Wind	20.0	20.0	20.0	20.0
R_e	1.678	1.673	1.678	1.673
-VaR	1.637	1.624	1.620	1.603
-CVaR	1.627	1.611	1.612	1.593
A2r, 820 ppm				
Coal	100.0	100.0	100.0	100.0
Biomass	0.0	0.0	0.0	0.0
Wind	0.0	0.0	0.0	0.0

(Continued)

Table 6.4 Continued

	$\beta = 95\%$, high σ^c	$\beta = 95\%$, low σ^c	$\beta = 99\%$, high σ^c	$\beta = 99\%$, low σ^c
R_e	1.778	1.778	1.778	1.778
-VaR	1.733	1.729	1.714	1.709
-CVaR	1.721	1.717	1.705	1.700

The table reports portfolio allocations (in %) for coal, biomass and wind, expected returns R_e, -CvaR and -VaR. The constraint on the lower bound on expected portfolio returns is not binding, all scenarios feature a 20 percent capacity constraint on biomass and wind.

A2r scenario. And for tougher stabilization targets, returns will be even lower. Industry will thus oppose the imposition of strict stabilization targets in our framework. Can policy makers adopt a less stringent target and still meet their goal of increasing the share of renewable energy and thereby reducing emissions?

In order to answer this question, we have to analyze the scenarios in more detail. In A2r, with the strict stabilization target and β = 95%, the low volatility portfolios are composed of 80 percent coal and 20 percent wind, as wind is the most attractive technology, but is restricted to the maximum of 20 percent and biomass is the most risky technology to invest into. However, as volatility increases, biomass returns increase above those of coal and also the -CVaR becomes almost equal to coal's (see Table 6.2). Therefore, the share of biomass in the portfolio increases from 0 to 15.9 percent at the expense of coal. When β is raised, however, the -CVaR of biomass decreases again and the portfolio share of biomass is reduced to 15.1 percent. Note that the portfolio return is higher and the (CVaR) risk lower for the more diversified portfolios, which is in line with our expectations and opens up more favorable prospects for industry as well. Similar patterns can be observed in the other scenarios.

Policy makers can thus conclude that—as long as they are not too extreme—fluctuations in the price of CO_2 are not necessarily detrimental to the achievement of their policy goals. Quite on the contrary, we have just seen that such volatility can lead to diversification of energy portfolios and adoption of renewable energy technologies, even in a world with such pessimistic outlooks as the A2r scenario—provided that a relatively strict target is envisaged. The latter is necessary to provide a large enough CO_2 price level during the course of the planning period, which triggers investment into less carbon-intensive power generation equipment. While industry would want to opt for a less strict target, which would ensure higher returns that are also more certain to materialize, emissions will not be reduced sufficiently and actually increase in all scenarios, as coal continues to dominate the generation mix. In that case, the policy does not serve its own purpose and should be updated.

5 Summary and policy implications

From the above analysis, it can be concluded that the new integrated portfolio and real options approach is a valuable tool to investigate the effects of carbon price volatility and different predictions about future circumstances on investment decisions at the firm level. This information can help larger investors providing finance to individual power generation projects to form beliefs about the timing of decisions and the resulting return distributions, which can then be used in a portfolio optimization. At the same time, non-normality of these return distributions requires the introduction of a new risk measure, the Conditional Value-at-Risk, which helps to capture information about the tail of these return distributions.

In general, the results correspond to our expectations: for the strict stabilization target, larger volatility leads to more diversification, higher returns and lower risk in B1, B2 and A2r. For the less strict stabilization target this is not the case. As CO_2 prices do not reach the trigger levels of investment, coal (and in B2 also wind) is the cheapest technology and the portfolio composition remains unchanged at 100 percent coal.

For policy making this implies that if we live in a world where CO_2 emissions reductions happen easily, as in the B1 world, and stabilization targets are not so ambitious, then fluctuations in the price of CO_2 allow big investors to realize large returns at low (-CVaR) risk, whereas stricter policy encourages retrofitting and thereby reduces profitability and increases risk. On the other hand, the latter will make the policy more efficient in terms of achieving stabilization targets: with stricter targets we always see diversification and so the adoption of more renewable energy. So while industry might favor a loose target, no matter which predictions they believe in about B1, B2 and A2r conditions, policy makers should remain committed to targets that generate emissions prices that will be able to trigger the investment that is necessary to reduce emissions. In addition, volatility in CO_2 prices affects individual power plant owners and thus reshapes the return distributions. Knowing this, large investors will diversify their portfolio and adopt more renewables. In other words, uncertainty at the firm level can make the policy designed to reduce emissions more successful, as the funds provided for energy generation are also spread out to biomass in our case.

Moreover, a larger confidence level generally makes portfolios more risky, which is self-explanatory by definition. If we want to interpret β as a kind of risk aversion measure, we may say that an increase in risk aversion in the face of large CO_2 price volatility leads to more diversification in the strict stabilization target situation in all three scenarios. With a less strict target this result does not hold, as has been mentioned before.

We think that this type of analysis opens up useful insights into investment dynamics. The optimal timing of investment and the exercise of investment and operational options are influenced by all kinds of price fluctuations. Here we have been focussing on electricity and CO_2 prices and on volatility in the growth of the latter in particular. Our framework is highly stylized and to be understood as a demonstration of a new methodology and its application to climate change policy. However, it has enabled us to investigate how volatility at the firm level affects investment and operational decisions and thereby returns, which then influences the beliefs of large investors, who will compose their portfolios accordingly. The following section will mention a few extensions that might be worthwhile to consider in future research.

6 Extensions

As the discussion above has shown, the integrated CVaR and real options approach is a useful tool in analyzing how optimum portfolios differ between different future scenarios and different policy parameters. However, our framework and also the data we use remain simple and rather general. On the one hand, this serves the purpose of illustrating a new methodology in a straightforward manner and free of too many interaction effects. On the other hand, we sacrifice a certain degree of realism. In order to apply the framework to specific situations, more details need to be taken into account and one should drop simplifying assumptions that could be decisive for the question at hand. For example, if construction times differ drastically between the technologies considered, this aspect has to be integrated into the real options model. Also, during the portfolio optimization more constraints might be needed. In addition, other technologies that have other defining characteristics and are also associated with other risks need to be analyzed. Nuclear energy is one candidate: while it may be much less prone to suffer from CO_2 price increases, decommissioning problems and uncertainty about security and maintenance might reduce its attractiveness again.

On the methodological side, there is one important extension that will be needed for long-term planning, and that is a dynamic version of the portfolio model. This is not a straightforward task because there are issues of consistency between the two procedures and also problems of cross effects and interdependence. As an example, if we regard the portfolio optimizer to be a big investor providing finance to the individual power plant investor, then the latter might update his/her decision on the basis of the actions of the former, which will again trigger a change in the optimization on the part of the big investor and so forth.

Appendix

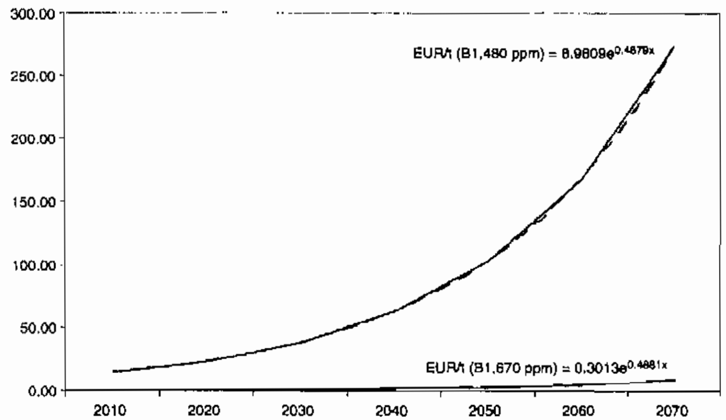

Figure 6A.1 Low population growth "optimistic" scenario.
Source: IIASA GGI database (2007).

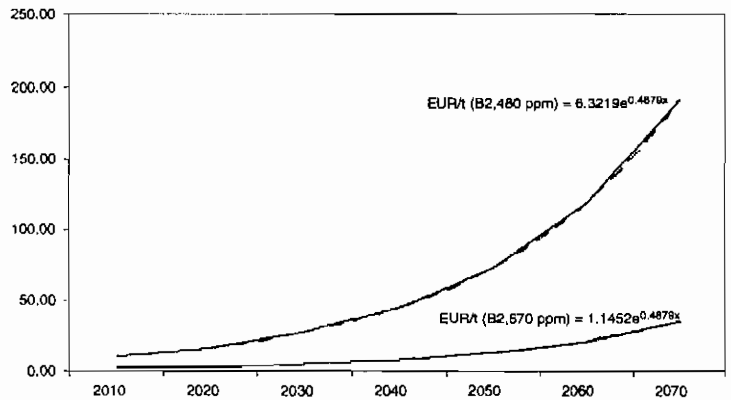

Figure 6A.2 "Intermediate" scenario.
Source: IIASA GGI database (2007).

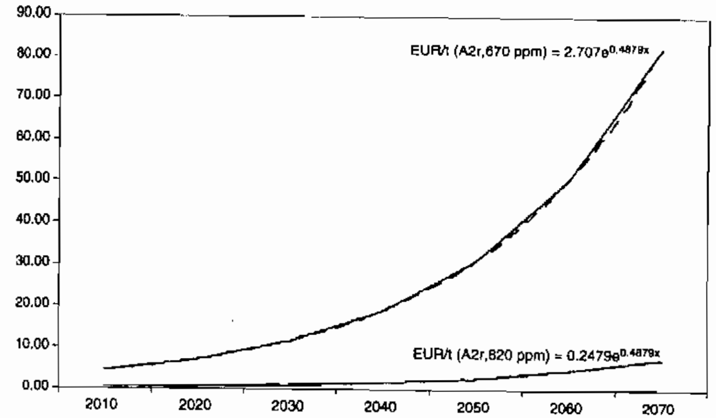

Figure 6A.3 High population growth "pessimistic" scenario.
Source: IIASA GGI database (2007).

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Notes

1 These damages involve, for example, the melting of the ice caps and glaciers leading to sea level rise and the destruction of the natural habitat of endangered species, ongoing desertification, more extreme weather situations involving higher intensity hurricanes, and many more (e.g. Knutson et al. (1998), Hulme and Kelly (1993), Overpeck et al. (2006), Rahmstorf (2007)).

2 See any standard textbook on portfolio theory for a more formal derivation of this result, e.g. Elton et al. (2003) or Brealey et al. (2005).

3 Furthermore, MV portfolios are myopic in the sense that the focus is on a portfolio at a single point in time. In electricity planning, planning periods of 30 years and more are usual, and dynamic developments call for a dynamic treatment of technology portfolios. While this problem has been tackled in the finance literature, these extensions are only applicable to financial assets so far. A study by van Zon and Fuss (2006) overcomes this problem by analyzing the generating portfolio in a vintage setting taking into account fuel and capital cost developments as well as fuel- and capital-saving technical change.

4 This definition only applies to continuous loss distributions. For the discrete case see Rockafellar and Uryasev (2002).

5 The CVaR approach can thus be viewed in some sense as a generalization of the MV approach when dealing with non-normal or non-symmetric distributions.

6 Note in particular that we value the investment options independently of each other, as otherwise the presence of the option to invest in one technology would

influence the value of another, which would obscure the results of the portfolio approach and therefore hamper our purpose to illustrate this new method in the most straightforward way.

7 Acknowledging that there are output contracts between distributors and generators, this assumption does not seem too strong.

8 See also Riahi et al. (2007) for a thorough description of these three scenarios and more details on the involved assumptions.

9 In any case, coal is not running out in the near future and thus leading to price increases due to scarcity, as thought in the past.

10 In the case where CCS is installed, output is lower due to lower efficiency, so producers will have to import the "deficit" at current spot market prices.

11 Uddin and Barreto (2007), amongst others, show that the negative emissions of a biomass-fired power plant with CCS are large, even if the decrease in efficiency, the extra emissions from the transport of biomass and CO_2 and many other factors are considered. According to their estimates, the emissions sequestered during the fuel growth phase are almost equal to the emissions produced by combusting it.

12 This refers to the number of Monte Carlo simulations for which investment is realized. The maximum number of times is thus 10,000.

13 In addition, the biomass CCS module is switched on and off much more frequently than the coal CCS module in the high volatility case.

14 See Fortin et al. (2007) for a more complete literature overview.

15 Note that minimizing the expected right tail loss (CVaR) is equivalent to maximizing the expected left tail return (-CVaR).

16 Problem (6.5) has efficiently been solved with GAMS (http://www.gams.com/) using the BDMLP and CONOPT solvers. The total number of equations in problem (5) is $q + n + 1$, the total number of constraints is $2q + n + 2$. The execution time for a sample size of $q = 10^4$ on a Pentium D 3.4 GHz computer running Windows XP Professional Version 2002 Service Pack 2, using GAMS version 2.0.30.1 is less than two minutes. Note that the computational complexity is defined by the complexity of the underlying mathematical model, which produces the sample to be fed into the LP problem-solving module, i.e. the real options model.

17 The choice of R is of course arbitrary here and will depend on the preferences of the concerned investor in other applications. Selecting a higher R will require the investor to accept a higher level of risk in terms of CVaR at the same time, so the risk-return tradeoff known from standard portfolio theory still applies.

References

Artzner, P., Delbaen, F., Eber, J.-M. and Heath, D. (1999) "Coherent Measures of Risk." *Mathematical Finance*, 9, 203–228.

Awerbuch, S. (2006) "Portfolio-based Electricity Generation Planning: Policy Implications for Renewables and Energy Security". *Mitigation and Adaptation Strategies for Global Change*, 11(3), 693–710.

Awerbuch, S., M. Berger (2003) "Applying Portfolio Theory to EU Electricity Planning and Policy-Making." Working Paper EET/2003/03, Paris: International Energy Agency.

Bar-Lev, D. and Katz, S. (1976) "A Portfolio Approach to Fossil Fuel Procurement in the Electric Utility Industry." *Journal of Finance*, 31(3), 933–942.

Black, F. and Scholes, M. (1973) "The Pricing of Options and Corporate Liabilities." *The Journal of Political Economy*, 81(3), 637–654.

Bogentoft, E., Romeijn, H. and Uryasev, S. (2001) "Asset/Liability Management for Pension Funds Using CVaR Constraints." *Journal of Risk*, 57–71.

Brealey, R., Myers, S. and Allen, F. (2005) *Principles of Corporate Finance*, McGraw Hill, 7th edn.

Chaton, C. and Doucet, J. (2003) "Uncertainty and Investment in Electricity Generation with an Application to the Case of Hydro-Quebec." *Annual Operations Research*, 120(1), 59–80.

Davis, G., and Owens, B. (2003) "Optimizing the Level of Renewable Electric R&D Expenditures Using Real Options Analysis." *Energy Policy*, 31, 1,589–1,608.

Deng, S., and Oren, S. (2003) "Incorporating Operational Characteristics and Start-up Costs in Option-based Valuation of Power Generation Capacity." *Probability in the Engineering and Informational Sciences*, 17(2), 155–181.

Dixit, A. and Pindyck, R. (1994) *Investment under Uncertainty*. Princeton: Princeton University Press.

Doege, J., Schiltknecht, P. and Lüthi, H.-J. (2006): "Risk Management of Power Portfolios and Valuation of Flexibility." *OR Spectrum*, 28, 267–287.

Elton, E., Gruber, M. and Brown, S. (2003) *Modern Portfolio Theory and Investment Analysis*. New York: Wiley, 6th edn.

Fama, E. (1970): "Multiperiod Consumption-Investment Decisions." *American Economic Review*, 60(1), 163–174.

Fichtner, W., Göbelt, M. and Rentz, O. (2002) "Ein Modell zur strategischen Investitions- und Produktionsplanung bei Energieversorgern unter Berücksichtung von Unsicherheiten." *ZfE—Zeitschrift für Energiewirtschaft*, 26(3), 181–192.

Fleten, S., Maribu, K. and Wangensteen, I. (2007) "Optimal Investment Strategies in Decentralized Renewable Power Generation under Uncertainty." *Energy*, 32(5), 803–815.

Fortin, I., Fuss, S., Hlouskova, J., Khabarov, N., Obersteiner, M. and Szolgayova, J. (2007) "An Integrated CVaR and Real Options Approach to Investments in the Energy Sector." Economics series no. 209, Vienna: Institute for Advanced Studies. Available at http://www.ihs.ac.at/publications/eco/es-209.pdf.

Helfat, C. (1988) *Investment Choices in Industry*. Cambridge, MA: MIT Press.

Hlouskova, J., Kossmeier, S., Obersteiner, M. and Schnabl, A. (2005) "Real Options and the Value of Generation Capacity in the German Electricity Market." *Review of Financial Economics*, 14(3–4), 297–310.

Hulme, M., and Kelly, M. (1993) "Exploring the Links Between Desertification and Climate Change." *Environment*, 35.

International Energy Agency (IEA) (2005) *Projected Costs of Generating Electricity 2005 Update*, Paris: OECD/Nuclear Energy Agency.

International Institute of Applied Systems Analysis (IIASA) (2007): "GGI Scenario Database." Available at http://www.iiasa.ac.at/Research/GGI/DB/.

Keppo, J. and Lu, H. (2003) "Real Options and a Large Producer: the Case of Electricity Markets." *Energy Economics*, 25(5), 459–472.

Knutson, T., Tuleya, R. and Kurihara, Y. (1998) "Simulated Increase of Hurricane Intensities in a CO_2-Warmed Climate." *Science*, 279, 1,018–1,021.

Krokhmal, P., Palmquist, J. and Uryasev S. (2001) "Portfolio Optimization with Conditional Value-at-Risk Objective and Constraints." *Journal of Risk*, 4(2), 43–68.

Krokhmal, P., Uryasev, S. and Zrazhevsky, G. (2005) "Numerical Comparison of Conditional Value-at-Risk and Conditional Drawdown-at-Risk Approaches: Application to Hedge Funds." In *Applications of Stochastic Programming*, ed. S. Wallace, and W. Ziemba, MPS-SIAM Series on Optimization. Society for Industrial & Applied Mathematics.

Liu, J., Men, C., Cabrera, V., Uryasev, S. and Fraisse, C. (2006) "CVaR Model for Optimizing Crop Insurance under Climate Variability." Discussion paper, Risk Management and Financial Engineering Lab, Department of Industrial and Systems Engineering University of Florida.

Madlener, R., Kumbaroglu, G. and Ediger, V. (2005) "Modelling Technology Adoption as an Irreversible Investment under Uncertainty: The Case of the Turkish Electricity Supply Industry." *Energy Economics*, 27(1), 139–163.

Markowitz, H. (1952): "Portfolio Selection." *Journal of Finance*, 7(1), 77–91.

McDonald, R., and Siegel. D. (1986): "The Value of Waiting to Invest." *Quarterly Journal of Economics*, 101, 707–723.

Merton, R.C. (1969): "Lifetime Portfolio Selection under Uncertainty: The Continuous-Time Case."*Review of Economics and Statistics*, 51(3), 247–257.

Merton, R. (1973): "The Theory of Rational Option Pricing." *Journal of Economic Management Science*, 4, 141–183.

Overpeck, J., Otto-Bliesner, B., Miller, G., Muhs, D., Alley, R. and Kiehl, J. (2006) "Paleoclimate Evidence for Future Ice-sheet Instability and Rapid Sea-level Rise." *Science*, 311, 1,747–1,750.

Pindyck, R. (1988) "Irreversible Investment, Capacity Choice, and the Value of the Firm." *American Economic Review*, 79, 969–985.

Pindyck, R. (1991) "Irreversibility, Uncertainty and Investment." *Journal of Economic Literature*, 29, 1,110–1,152.

Pindyck, R. (1993) "Investments of Uncertain Cost." *Journal of Financial Economics*, 34, 53–76.

Rahmstorf, S. (2007) "A Semi-empirical Approach to Projecting Future Sea-level Rise." *Science*, 315, 368–370.

Reinelt, P.S. and D.W. Keith (2007) "Carbon Capture Retrofits and the Cost of Regulatory Uncertainty." *Energy Journal*, 28, 101–127.

Riahi, K., Grübler, A. and Nakicenovic, N. (2007) "Scenarios of Long-term Socio-economic and Environmental Development under Climate Stabilization." *Technological Forecasting and Social Change*, 47, 887–935.

Rockafellar, R. and Uryasev, S. (2000) "Optimization of Conditional Value at Risk." *Journal of Risk*, 2, 21–42.

Rockafellar, R. and Uryasev, S. (2002) "Conditional Value at Risk for General Loss Distributions." *Journal of Banking and Finance*, 26, 1,443–1,471.

Roques, F., Newbery, D. and Nuttall, W. (2006) "Fuel Mix Diversification Incentives in Liberalized Electricity Markets: A Mean-Variance Portfolio Approach." Working Paper 2006/33, RCAS of the European University Institute: Florence School of Regulation.

Samuelson, P. (1969) "Lifetime Portfolio Selection by Dynamic Stochastic Programming." *Review of Economics and Statistics*, 51(3), 239–246.

Schnitkey, G., Sherrick, B. and Irwin, S. (2004) "The Performance of Conditional Value-at-Risk versus Value-at-Risk in Ranking Crop Insurance Alternatives." Discussion paper, Department of Agricultural and Consumer Economics University of Illinois at Urbana-Champaign.

Schwartz, E. and Trigeorgis, L. (2001) *Real Options and Investment under Uncertainty: Classical Readings and Recent Contributions*. Cambridge, MA: MIT Press.

Spangardt, G., Lucht, M., and Handschin, E. (2006) "Applications for stochastic optimization in the power industry." *Electrical Engineering*, 88, 177–182.

Topaloglou, N., Vladimirou, H. and Zenios, S. (2003) "CVaR Models with Selective Hedging for International Asset Allocation." *Journal of Banking and Finance*, 26(7), 1,535–1,561.

Trigeorgis, L. (1996) *Real Options: Managerial Flexibility and Strategy in Resource Allocation*, Cambridge, MA: MIT Press.

Tseng, C. and Barz, G. (2002) "Short-term Generation Asset Valuation: A Real Options Approach." *Operations Research*, 50(2), 297–310.

Uddin, S. and Barreto, L. (2007) "Biomass-fired Cogeneration Systems with CO_2 Capture and Storage." *Renewable Energy*, 32, 1,006–1,019.

Unger, G. and Lüthi, H.-J. (2002) "Power Portfolio Optimization and the Importance of Operational Flexibility." Discussion paper, IFOR, ETH Zentrum.

Van Zon, A. and Fuss, S. (2006) "Irreversible Investment under Uncertainty in Electricity Generation: a Clay-Clay-Vintage Portfolio Approach with an Application to Climate Change Policy in the UK." Working Paper 2006–035, UNU-MERIT.

Valuing Climate Change Uncertainty Reductions for Robust Energy Portfolios**

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Abstract – Climate policy uncertainty has decisive influence on energy sector strategies. Potential stranded climate-energy investments may be enormous. Remote sensing can improve our understanding of the climate system and thus better inform climate policy and reduce associated uncertainties. We develop an integrated energy-portfolio model to value these uncertainties. The operations of individual power plants are optimized using real options given scenarios of stochastically evolving CO_2 prices mimicking observation-induced climate policy uncertainty. The resulting profit distributions are used in a portfolio optimization. The optimization under imperfect information about future CO_2 prices leads to substantially lower profits for a given risk level when portfolios are to be robust across all plausible scenarios. A potential uncertainty reduction associated with an improved climate modeling supported by remote sensing will thus not only lead to substantial financial efficiency gains, but will also be conducive to steering investments into the direction of higher shares of renewable energy.

Keywords: real options, energy, policy uncertainty, robust portfolios, Earth observations.

1. INTRODUCTION

The arrival of better information and new data from remote sensing on climate sensitivity and other factors important for determining the necessary stabilization target and corresponding policy measures often leads to adaptations and adjustments in the latter and therefore to considerable uncertainty for investors in the energy sector. In a recent article, Hansen et al (2008) explain that paleoclimate evidence and ongoing climate change suggest that CO_2 will need to be reduced to much lower levels than we might have been prepared for. They claim that "the largest uncertainty in the target arises from possible changes of non-CO_2 forcings." Remote sensing can help to monitor GHGs and compare actual to reported emissions and computed scenarios. Numerical models can then be used to examine their impact on radiative forcing, which can then be translated to the appropriate policies.

1.1 Motivation

The energy sector is characterized by long-lived investments involving large sunk costs. Once a power plant, for example, is installed, it will most probably be used throughout its lifetime and maybe even beyond. Many OECD countries are now in the situation, however, that existing capacity is ageing and much of it will need to be replaced in the coming decades. In order to avoid further lock-in to fossil-fuel-based energy technologies, policymakers have been trying to incentivise a transition to a less carbon-intensive energy production regime by imposing taxes on the combustion of fossil fuels or through a cap-and-trade system with tradable permits within the European Union (EU).

In this paper we want to shed more light on decision-making in the electricity sector when investors are faced with uncertainty about CO_2 policy. This will show how important Earth observations are for better-informed decisions. To this end, we develop a new framework of analysis, where different methodologies are integrated: the investment decisions and operations at the plant level are optimized within a real options framework. This provides the profit distributions that will in turn inform the larger investor (i.e. a larger energy company, a region or even a country) of how to diversify across technologies. For this part of the analysis we have chosen a portfolio approach, which will use the Conditional Value-at-Risk (CVaR) as a risk-measure, since the more common variance approach should only be used in cases where the profit distributions are clearly normal, which does not apply in our case.
This approach builds on earlier work by Fortin et al (2008), but has one important novelty that enables us to evaluate the impact of policy uncertainty or, in other words, the value of better information. More precisely, we compute the losses from being forced to have an energy portfolio, which is robust across different scenarios. The scenarios are characterized by differences in the CO_2 price, which again depend upon the stabilization target chosen.

1.2 References to Related Work

The electricity sector bears certain features, which makes real options analysis in this context a suitable tool for investment decision-making. In particular, these features pertain to the flexibility on behalf of the investor to time the commitment of large resources optimally in the face of uncertainty about future developments (see Dixit and Pindyck (1994) for a more complete overview, also on methodological issues). Especially studies concerned with the effect of policy uncertainty have recently surged: Fuss et al (2009) use a real options model where multiple options are evaluated simultaneously, so that the effect of the individual options on each other is accounted for. The model is applied to the electricity sector, analyzing the transition from CO_2-intensive to CO_2-neutral electricity production in the face of rising and uncertain CO_2 prices and estimating the expected value of (perfect) information, i.e. the willingness of investors and producers to pay for information about the correct CO_2 price path, which rises over time. The authors find that it is preferable to have climate change policies that are stable over a certain length of time, since less frequent fluctuations reduce the expected value of information and result in smaller cumulative CO_2 emissions. Other studies are presented in an International Energy Agency book (IEA, 2007). Similarly, Reinelt and Keith (2006) employ real options to assess energy investments, where they focus on the social cost of CO_2 price uncertainty, which they find to be enhanced by investment irreversibility and alleviated by the competitiveness of technologies with relatively inexpensive carbon capture retrofit possibilities.

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While such real options models are well suited for optimization of timing of investment and operations at the plant level, larger investors typically want to reduce risks by diversification. Portfolio frameworks have therefore been widely applied to energy sector investment before (see Bazilian and Roque (2008) for a compendium of the existing literature and the latest developments in this field).

The combination of real options modeling and portfolio optimization as such had first been implemented by Fortin et al (2008). The current paper is an extension of this work in the sense that it deals with the optimization of portfolios, which are robust across different scenarios, which can entail considerable losses depending on which scenario really materializes. Our findings indeed prove that better information about climate sensitivity and forcing by non-GHG gases leading to more stable climate policy can provide for substantial gains in terms of expected profits and reduced risks.

2. MODELING FRAMEWORK

2.1 Technologies Considered & Real Options Model

In this study we are looking at two different types of technologies that can be retrofitted with carbon capture (CCS) modules: a coal-fired power plant and a biomass-fired power plant, where the former stands representative for the fossil-fuel-fired energy technologies and the latter for renewable energy carriers, even though biomass-fired power production has the special feature that the fuel generation itself already sequesters as many emissions as are produced during combustion. Adding carbon capture facilities can thus result in *negative* emissions (Uddin and Barreto, 2007). Table A lists the relevant data of both technologies.

Table A. Power Plant Data (Source: IEA/OECD, 2005)

Parameters	Coal	Coal+CCS	Bio	Bio+CCS
Output (MWh/yr)	7,446	6,475	7,446	6,475
CO_2 (t CO_2/yr)	6,047	576	0	-6,100
Fuel Cost (€/yr)	39,510	39,510	152,612	152,612
O&M (€/yr)	43,710	60,110	43,269	59,669
Installed Cap. (MW)	1	1	1	1
Capital Cost (1,000€)	1,373	1,716	1,537	1,880

In the real options model the optimal investment plan for a single profit-maximizing electricity producer facing stochastic CO_2 prices is computed, thereby generating the profit distributions for the portfolio model. The producer has to deliver a certain amount of electricity over the course of the planning period.

For a full overview of this model, the reader is referred to earlier work in Fortin et al (2008). For the sake of saving space we will present the main equation only and describe the relevant parameters/scenarios.

The real options model considers a power plant owner with existing capacity that expires in 50 years, who has to decide, when or whether to add and how to operate an CCS module. We assume the decisions can be done on a yearly basis. The problem the investor is facing can be formulated as an optimal control problem with the investor seeking to determine his actions for each year (as a function of current state and carbon price) maximizing his profits subject to stochastic CO_2 price following a Geometric Brownian Motion (GBM) in order to allow for an upward-trending, but fluctuating price path:

$$dP_t^c = \mu^c \cdot P_t^c dt + \sigma^c \cdot P_t^c \cdot dW_c^t \qquad (1)$$

with μ^c being the drift and σ^c the volatility parameter and W_t^c is the increment of a Wiener process. Let us define the yearly profit of the investor $\pi(\bullet)$ as a functions of the current state (denoted by x, representing whether the CCS module has been installed and whether it's running), the current CO_2 price and the action undertaken in that year (denoted by a). Actions available are either to do nothing or install the CCS module (in case it has not been installed yet) or to switch the module on or off (in case it has already been installed). The profit is equal to the income from selling electricity less the cost associated with running the plant and the cost of actions undertaken in that year.

The optimal control problem can be solved recursively by dynamic programming, where the corresponding Bellman equation is:

$$\begin{aligned} V(x_t, P_t^c) = \max_{a \in A(x_t)} \{ \pi(x_t, a(x_t, P_t^c), P_t^c) + \\ + e^{-r} E[V(x_{t+1}, P_{t+1}^c) \big| x_t, P_t^c] \} \end{aligned} \qquad (2)$$

$V(\bullet)$ is the value function; T=50 is the planning horizon. V equals zero at the end of the plant's lifetime.

The optimization problem can then be solved recursively. The first part of the sum in equation (2) is the immediate profit upon investment; the second part is the value from waiting, which is computed using Monte Carlo simulation. This method was chosen, since it remains computationally efficient for a high degree of complexity and is rather precise when the discretization of the price is sufficiently fine. The output of the recursive optimization part is a table listing the optimal action for each time period, for each possible state and for each possible carbon price in that period. For the analysis of the final outcome, we can then simulate (10,000) possible CO_2 price paths and extract the corresponding decisions from the output table. By plotting the profits for all 10,000 price paths, we obtain the final distributions needed.

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Defining CVaR according to Rockafellar and Uryasev (2000), let f(x,y) be the loss function depending on the investment strategy $x \in \Re^n$ and the random vector $y \in \Re^m$, and let p(y) be the density of y. The probability of f(x,y) not exceeding some fixed threshold level α is $\psi(x,\alpha) = \int_{f(x,y)\le\alpha} p(y)dy$. The β-VaR is defined by $\alpha_\beta(x) = \min\{\alpha \mid \psi(x,\alpha) \ge \beta\}$ and the β-CVaR is defined by $CVaR_\beta(x) = \phi_\beta(x) = (1-\beta)^{-1} \int_{f(x,y)\ge\alpha_\beta(x)} f(x,y)p(y)dy$, which is the expected loss given that it exceeds the β-VaR level, where β is the confidence level. Both VaR and CVaR are applicable to profits as well as to losses, because one may consider returns as negative losses (and losses as negative returns). In the following, losses are defined as negative returns and thus we will report -VaR and -CVaR to indicate respectively the lower threshold for returns and expected returns in case they are lower than that threshold.

Let us consider n different technologies (here two) for investment. Values y_i, i = 1,…,n reflect the profits for each technology. We assume the vector y = $[y_1,\ldots, y_n]^T \in \Re^n$ of NPV profits to be a random vector having some distribution and describe the investment strategy using the vector x = $[x_1,\ldots, x_m]T \in \Re^n$, where the scalar value x_i reflects the fraction of capital invested into technology i. The return function depends on the chosen investment strategy and the actual profits; computed as $x^T y$. As the actual profit is unknown, there is a specific degree of risk associated with investment strategy x. To measure this risk and find the corresponding optimal *x*, our optimization is based on minimizing CVaR with a loss function $f(x, y) = - x^T y$, i.e. negative profits. Following Rockafellar and Uryasev (2000), we approximate the problem of minimizing CVaR by solving a piece-wise linear programming problem and reduce this to a linear programming problem with auxiliary variables. A sample $\{y_k\}^q_{k=1}$, $y_k \in \Re^n$ of the profit distribution is used to construct the LP problem. Concerning the investment strategy in the sense that it should deliver a specified minimum expected profit (or limited expected loss), the LP problem is equivalent to finding the investment strategy minimizing risk in terms of CVaR:

$$\begin{aligned}
&\min_{(x,\alpha,u)} \alpha + \frac{1}{q(1-\beta)} \sum_{k=1}^{q} u_k \\
&\text{s.t. } e^T x = 1, m^T x \geq \pi, x \geq 0, u_k \geq 0, \\
&y_k^T x + \alpha + u_k \geq 0,\ k = 1,\dots,q\ .
\end{aligned} \tag{3}$$

where $u_k \in \Re^n$, k=1,…,q are auxiliary variables, $e \in \Re^n$ is a vector of ones, q is the sample size, $m=E(y) \in \Re^n$ is the expectation of the profit vector. π is the minimum portfolio profit[1] and α the threshold of the loss function β.

Now let us consider a problem similar to (3), where the sample $(y_{ks})^q_{k=1}$, $y_{ks} \in \Re^n$ of the profit distribution depends on the scenario number s=1,…,S. We consider a minimax setup, where an investor wants to hedge against the worst possible.

$$\begin{aligned}
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&k = 1,\dots,q,\ s = 1,\dots,S.
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$$\beta - \text{CVaR}(x_*) = \min_x \max_s \beta - \text{CVaR}_s(x). \tag{5}$$

3. RESULTS: ENERGY SECTOR LOSSES DUE TO UNCERTAINTY

3.1 Scenarios Considered and Parameters

Table B. Parameters

μ^c			P_0^c (€/ton)	σ^c	r
scen.1	scen.2	scen.3			
0.00636	0.01716	0.0397	12	0.04	0.05

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[1] The values for required expected profit are in fact not binding: setting required profits high would exclude technologies that could have been interesting alternatives from the point-of-view of their risk profiles.

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Table C presents the results from the real options optimization – the characteristics of the profit distributions in terms of payoff and risk. Note that we report the –CVaR here; the variance is actually increasing for biomass as stabilization targets get stricter.

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	Coal		Biomass	
Scenario	Exp. Profit (10^6 €)	-CVaR (97%)	Exp. Profit (10^6 €)	-CVaR (97%)
1	1.177	1.050	0.523	0.228
2	1.099	1.007	0.808	0.351
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It is clear that coal is the more profitable technology for looser targets (scenario 1) and biomass gets more attractive only as CO_2 prices increase more rapidly. Therefore, it does not come as a surprise that the portfolio in scenario 1 is dominated by coal. For scenarios 2 and 3 the target gets stricter and the share of biomass grows (see Fig. 1).

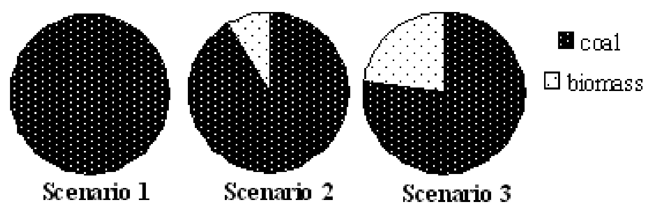

Figure 1. Portfolio shares per scenario.

3.1 Minimax Portfolios

Table C summarizes the outcomes for optimizing portfolios that are either based on the expectations of one scenario (the benchmark case) or that have to be robust across 2-3 scenarios.

Table D. Expected profits in 10^6 € and –CVaR risk (*robust across these scenarios)

	actual scenario					
	1		2		3	
*	exp. profit	-CVaR	exp. profit	-CVaR	exp. profit	-CVaR
1	1.177	1.061	1.099	1.021	0.984	0.871
2	1.121	1.046	1.075	1.05	1.056	1.049
3	1.03	0.963	1.034	0.979	1.176	1.062
12	1.126	1.049	1.077	1.049	1.05	1.034
13	1.122	1.047	1.075	1.05	1.055	1.047
23	1.121	1.046	1.074	1.05	1.057	1.05
123	1.122	1.047	1.075	1.05	1.055	1.047

Fig. 2 shows three different portfolio profits in three different scenarios to make these results more transparent. The first bar in each scenario (dotted) refers to the portfolio, which has been optimized for the first scenario only (i.e. the benchmark case from the previous section). Obviously, this one performs best in the scenario that it has been optimized for, therefore. Should scenarios

2 or 3 materialize, profits will be progressively smaller. This already underlines the importance of having the right information for finding the optimal portfolio. The second bar (checked) represents the portfolio, which is robust across the first and the second scenario, where the latter involves a stricter stabilization target. This one also performs best in the first scenario, but the drop if scenarios 2 or 3 turn out to be the case is smaller relative to the "non-robust" portfolio. This effect is even more pronounced for the portfolio, which has to be robust across all three scenarios (diamond pattern).

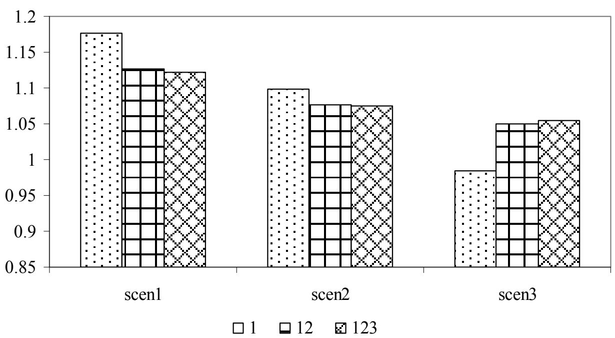

Figure 2. Expected profit (in 10^6 €) across scenarios (scen).

These results show that robust portfolio optimization in the form of our minimax-approach is a valuable tool to reduce the impact of missing information: should other scenarios than expected materialize, the investor who has optimized only for scenario 1 will experience a much larger drop in profits than the one that has been using the minimax-criterion. However, this "security" comes at the cost of accepting lower overall profits in the first two scenarios. It is thus clear that missing information causing uncertainty about stabilization targets or the adaptation of a target due to a prior lack of data leads to optimization under imperfect information and thus large losses in profits. Table D furthermore confirms that the robust portfolios perform better in terms of lower –CVaR risk in the alternative scenarios.

From a policymaker's perspective it is also interesting to note that the robust portfolios all have shares of biomass below 10%, which indicates that even if scenario 3 would have been a possibility, the chance that the other scenarios might also turn out to be true drives down investment in biomass. This further stresses the need for more precise data and information that enable the formulation of a clear and transparent stabilization target, which will not have to be adapted drastically.

4. CONCLUSION

A lack of information and data, which could be overcome through remote sensing, causes uncertainty about the appropriate stabilization target that policymakers have to base their decisions concerning climate policy upon. The EU has established a permit trading scheme, where the price rises and is inherently unstable. We have tried to model this situation by letting the CO_2 price follow a stochastic process (a GBM) and computed profit distributions for two types of power plants that are exposed to CO_2 price fluctuations to a different extent, so that diversification considerations would lead them to adopt renewable energy for stricter targets, while loose targets favor a fossil-fuel-dominated portfolio. A portfolio optimization using these profit distributions as input, has shown that expected profits are prone to drop substantially, if a scenario different from the one used in the optimization turns out to become reality. Robust portfolios (using a minimax-criterion) can partly overcome this problem by minimizing this drop, but this goes at the expense of higher profits in most scenarios. In other words, the investor has to accept low profits for relatively small improvements in risk.

It is clear that it is therefore of paramount importance to obtain the best information possible about climate sensitivity, changes in non-CO_2 forcing and the correspondence between actual and reported CO_2 emissions to come up with a clear and stable target and enable optimization under the most complete information possible.

REFERENCES

M. Bazilian, F. Roques, "Analytical Methods for Energy Diversity and Security," A Tribute the work of Dr Shimon Awerbuch. Elsevier, Oxford, 1 edn., 2008.

I. Fortin, S. Fuss, J. Hlouskova, N. Khabarov, M. Obersteiner, J. Szolgayova, "An integrated CVaR and real options approach to investments in the energy sector," The Journal of Energy Markets, vol. 1, p.p. 61-85, 2008.

S. Fuss, D. J. A. Johansson, J. Szolgayova, M. Obersteiner, "Impact of climate policy uncertainty on the adoption of electricity generating technologies," Energy Policy, vol. 37, p.p. 733-743, 2009.

J. Hansen, Mki. Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson-Delmotte, M. Pagani, M. Raymo, D.L. Royer, and J.C. Zachos, "Target atmospheric CO_2: Where should humanity aim?" Open Atmos. Sci. J., vol. 2, p.p. 217-231, 2008.

International Energy Agency, "Climate Policy Uncertainty and Investment Risk," IEA/OECD: Paris, France, 2007.

International Energy Agency, "Projected Costs of Generating Electricity 2005 Update," OECD Nuclear Energy Agency, Paris, 2005.

International Institute of Applied Systems Analysis (IIASA), 2007. GGI Scenario Database, Laxenburg, Austria, available at http://www.iiasa.ac.at/Research/GGI/DB/.

P.S. Reinelt, D.W. Keith, "Carbon capture retrofits and the cost of regulatory uncertainty," Energy Journal vol. 28, p.p. 101-127, 2007.

R. Rockafellar, S. Uryasev, "Optimization of Conditional Value at Risk," Journal of Risk, vol.2, p.p. 21-42, 2000.

S. Uddin, L. Barreto, "Biomass-fired Cogeneration Systems with CO_2 Capture and Storage," Renewable Energy, vol.32, p.p. 1006-1019, 2007.

Valuing Climate Change Uncertainty Reductions for Robust Energy Portfolios

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Abstract – Climate policy uncertainty has decisive influence on energy sector strategies. Potential stranded climate-energy investments may be enormous. Remote sensing can improve our understanding of the climate system and thus better inform climate policy and reduce associated uncertainties. We develop an integrated energy-portfolio model to value these uncertainties. The operations of individual power plants are optimized using real options given scenarios of stochastically evolving CO_2 prices mimicking observation-induced climate policy uncertainty. The resulting profit distributions are used in a portfolio optimization. The optimization under imperfect information about future CO_2 prices leads to substantially lower profits for a given risk level when portfolios are to be robust across all plausible scenarios. A potential uncertainty reduction associated with an improved climate modeling supported by remote sensing will thus not only lead to substantial financial efficiency gains, but will also be conducive to steering investments into the direction of higher shares of renewable energy.

Keywords: real options, energy, policy uncertainty, robust portfolios, Earth observations.

1. INTRODUCTION

The arrival of better information and new data from remote sensing on climate sensitivity and other factors important for determining the necessary stabilization target and corresponding policy measures often leads to adaptations and adjustments in the latter and therefore to considerable uncertainty for investors in the energy sector. In a recent article, Hansen et al (2008) explain that paleoclimate evidence and ongoing climate change suggest that CO_2 will need to be reduced to much lower levels than we might have been prepared for. They claim that "the largest uncertainty in the target arises from possible changes of non-CO_2 forcings." Remote sensing can help to monitor GHGs and compare actual to reported emissions and computed scenarios. Numerical models can then be used to examine their impact on radiative forcing, which can then be translated to the appropriate policies.

1.1 Motivation

The energy sector is characterized by long-lived investments involving large sunk costs. Once a power plant, for example, is installed, it will most probably be used throughout its lifetime and maybe even beyond. Many OECD countries are now in the situation, however, that existing capacity is ageing and much of it will need to be replaced in the coming decades. In order to avoid further lock-in to fossil-fuel-based energy technologies, policymakers have been trying to incentivise a transition to a less carbon-intensive energy production regime by imposing taxes on the combustion of fossil fuels or through a cap-and-trade system with tradable permits within the European Union (EU).

In this paper we want to shed more light on decision-making in the electricity sector when investors are faced with uncertainty about CO_2 policy. This will show how important Earth observations are for better-informed decisions. To this end, we develop a new framework of analysis, where different methodologies are integrated: the investment decisions and operations at the plant level are optimized within a real options framework. This provides the profit distributions that will in turn inform the larger investor (i.e. a larger energy company, a region or even a country) of how to diversify across technologies. For this part of the analysis we have chosen a portfolio approach, which will use the Conditional Value-at-Risk (CVaR) as a risk-measure, since the more common variance approach should only be used in cases where the profit distributions are clearly normal, which does not apply in our case.

This approach builds on earlier work by Fortin et al (2008), but has one important novelty that enables us to evaluate the impact of policy uncertainty or, in other words, the value of better information. More precisely, we compute the losses from being forced to have an energy portfolio, which is robust across different scenarios. The scenarios are characterized by differences in the CO_2 price, which again depend upon the stabilization target chosen.

1.2 References to Related Work

The electricity sector bears certain features, which makes real options analysis in this context a suitable tool for investment decision-making. In particular, these features pertain to the flexibility on behalf of the investor to time the commitment of large resources optimally in the face of uncertainty about future developments (see Dixit and Pindyck (1994) for a more complete overview, also on methodological issues). Especially studies concerned with the effect of policy uncertainty have recently surged: Fuss et al (2009) use a real options model where multiple options are evaluated simultaneously, so that the effect of the individual options on each other is accounted for. The model is applied to the electricity sector, analyzing the transition from CO_2-intensive to CO_2-neutral electricity production in the face of rising and uncertain CO_2 prices and estimating the expected value of (perfect) information, i.e. the willingness of investors and producers to pay for information about the correct CO_2 price path, which rises over time. The authors find that it is preferable to have climate change policies that are stable over a certain length of time, since less frequent fluctuations reduce the expected value of information and result in smaller cumulative CO_2 emissions. Other studies are presented in an International Energy Agency book (IEA, 2007). Similarly, Reinelt and Keith (2006) employ real options to assess energy investments, where they focus on the social cost of CO_2 price uncertainty, which they find to be enhanced by investment irreversibility and alleviated by the competitiveness of technologies with relatively inexpensive carbon capture retrofit possibilities.

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While such real options models are well suited for optimization of timing of investment and operations at the plant level, larger investors typically want to reduce risks by diversification. Portfolio frameworks have therefore been widely applied to energy sector investment before (see Bazilian and Roque (2008) for a compendium of the existing literature and the latest developments in this field).

The combination of real options modeling and portfolio optimization as such had first been implemented by Fortin et al (2008). The current paper is an extension of this work in the sense that it deals with the optimization of portfolios, which are robust across different scenarios, which can entail considerable losses depending on which scenario really materializes. Our findings indeed prove that better information about climate sensitivity and forcing by non-GHG gases leading to more stable climate policy can provide for substantial gains in terms of expected profits and reduced risks.

2. MODELING FRAMEWORK

2.1 Technologies Considered & Real Options Model

In this study we are looking at two different types of technologies that can be retrofitted with carbon capture (CCS) modules: a coal-fired power plant and a biomass-fired power plant, where the former stands representative for the fossil-fuel-fired energy technologies and the latter for renewable energy carriers, even though biomass-fired power production has the special feature that the fuel generation itself already sequesters as many emissions as are produced during combustion. Adding carbon capture facilities can thus result in *negative* emissions (Uddin and Barreto, 2007). Table A lists the relevant data of both technologies.

Table A. Power Plant Data (Source: IEA/OECD, 2005)

Parameters	Coal	Coal+CCS	Bio	Bio+CCS
Output (MWh/yr)	7,446	6,475	7,446	6,475
CO_2 (t CO_2/yr)	6,047	576	0	-6,100
Fuel Cost (€/yr)	39,510	39,510	152,612	152,612
O&M (€/yr)	43,710	60,110	43,269	59,669
Installed Cap. (MW)	1	1	1	1
Capital Cost (1,000€)	1,373	1,716	1,537	1,880

In the real options model the optimal investment plan for a single profit-maximizing electricity producer facing stochastic CO_2 prices is computed, thereby generating the profit distributions for the portfolio model. The producer has to deliver a certain amount of electricity over the course of the planning period.

For a full overview of this model, the reader is referred to earlier work in Fortin et al (2008). For the sake of saving space we will present the main equation only and describe the relevant parameters/scenarios.

The real options model considers a power plant owner with existing capacity that expires in 50 years, who has to decide, when or whether to add and how to operate an CCS module. We assume the decisions can be done on a yearly basis. The problem the investor is facing can be formulated as an optimal control problem with the investor seeking to determine his actions for each year (as a function of current state and carbon price) maximizing his profits subject to stochastic CO_2 price following a Geometric Brownian Motion (GBM) in order to allow for an upward-trending, but fluctuating price path:

$$dP_t^c = \mu^c \cdot P_t^c dt + \sigma^c \cdot P_t^c \cdot dW_c^t \tag{1}$$

with μ^c being the drift and σ^c the volatility parameter and W_t^c is the increment of a Wiener process. Let us define the yearly profit of the investor $\pi(\bullet)$ as a functions of the current state (denoted by x, representing whether the CCS module has been installed and whether it's running), the current CO_2 price and the action undertaken in that year (denoted by a). Actions available are either to do nothing or install the CCS module (in case it has not been installed yet) or to switch the module on or off (in case it has already been installed). The profit is equal to the income from selling electricity less the cost associated with running the plant and the cost of actions undertaken in that year.

The optimal control problem can be solved recursively by dynamic programming, where the corresponding Bellman equation is:

$$\begin{aligned} V(x_t, P_t^c) = \max_{a \in A(x_t)} \{\pi(x_t, a(x_t, P_t^c), P_t^c) + \\ + e^{-r} E[V(x_{t+1}, P_{t+1}^c) | x_t, P_t^c]\} \end{aligned} \tag{2}$$

$V(\bullet)$ is the value function; T=50 is the planning horizon. V equals zero at the end of the plant's lifetime.

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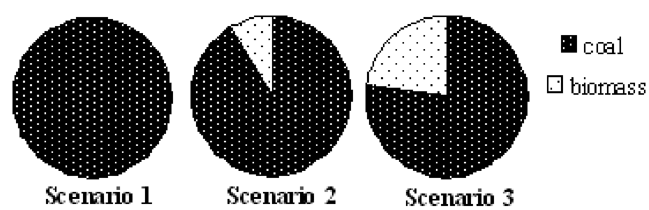

Figure 1. Portfolio shares per scenario.

3.1 Minimax Portfolios

Table C summarizes the outcomes for optimizing portfolios that are either based on the expectations of one scenario (the benchmark case) or that have to be robust across 2-3 scenarios.

Table C. Expected profits in 10^6 € and –CVaR risk (*robust across these scenarios)

	actual scenario					
	1		2		3	
*	exp. profit	-CVaR	exp. profit	-CVaR	exp. profit	-CVaR
1	1.177	1.061	1.099	1.021	0.984	0.871
2	1.121	1.046	1.075	1.05	1.056	1.049
3	1.03	0.963	1.034	0.979	1.176	1.062
12	1.126	1.049	1.077	1.049	1.05	1.034
13	1.122	1.047	1.075	1.05	1.055	1.047
23	1.121	1.046	1.074	1.05	1.057	1.05
123	1.122	1.047	1.075	1.05	1.055	1.047

Fig. 2 shows three different portfolio profits in three different scenarios to make these results more transparent. The first bar in each scenario (dotted) refers to the portfolio, which has been optimized for the first scenario only (i.e. the benchmark case from the previous section). Obviously, this one performs best in the scenario that it has been optimized for, therefore. Should scenarios 2 or 3 materialize, profits will be progressively smaller. This already underlines the importance of having the right information for finding the optimal portfolio. The second bar (checked) represents the portfolio, which is robust across the first and the second scenario, where the latter involves a stricter stabilization target. This one also performs best in the first scenario, but the drop if scenarios 2 or 3 turn out to be the case is smaller relative to the "non-robust" portfolio. This effect is even more pronounced for the portfolio, which has to be robust across all three scenarios (diamond pattern).

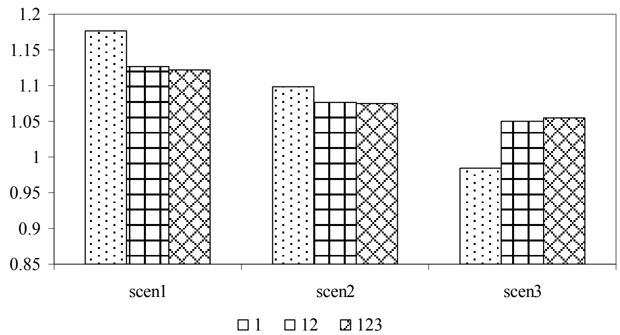

Figure 2. Expected profit (in 10^6 €) across scenarios (scen).

These results show that robust portfolio optimization in the form of our minimax-approach is a valuable tool to reduce the impact of missing information: should other scenarios than expected materialize, the investor who has optimized only for scenario 1 will experience a much larger drop in profits than the one that has been using the minimax-criterion. However, this "security" comes at the cost of accepting lower overall profits in the first two scenarios. It is thus clear that missing information causing uncertainty about stabilization targets or the adaptation of a target due to a prior lack of data leads to optimization under imperfect information and thus large losses in profits. Table D furthermore confirms that the robust portfolios perform better in terms of lower –CVaR risk in the alternative scenarios.

From a policymaker's perspective it is also interesting to note that the robust portfolios all have shares of biomass below 10%, which indicates that even if scenario 3 would have been a possibility, the chance that the other scenarios might also turn out to be true drives down investment in biomass. This further stresses the need for more precise data and information that enable the formulation of a clear and transparent stabilization target, which will not have to be adapted drastically.

4. CONCLUSION

A lack of information and data, which could be overcome through remote sensing, causes uncertainty about the appropriate stabilization target that policymakers have to base their decisions concerning climate policy upon. The EU has established a permit trading scheme, where the price rises and is inherently unstable. We have tried to model this situation by letting the CO_2 price follow a stochastic process (a GBM) and computed profit distributions for two types of power plants that are exposed to CO_2 price fluctuations to a different extent, so that diversification considerations would lead them to adopt renewable energy for stricter targets, while loose targets favor a fossil-fuel-dominated portfolio. A portfolio optimization using these profit distributions as input, has shown that expected profits are prone to drop substantially, if a scenario different from the one used in the optimization turns out to become reality. Robust portfolios (using a minimax-criterion) can partly overcome this problem by minimizing this drop, but this goes at the expense of higher profits in most scenarios. In other words, the investor has to accept low profits for relatively small improvements in risk.

It is clear that it is therefore of paramount importance to obtain the best information possible about climate sensitivity, changes in non-CO_2 forcing and the correspondence between actual and reported CO_2 emissions to come up with a clear and stable target and enable optimization under the most complete information possible.

REFERENCES

M. Bazilian, F. Roques, "Analytical Methods for Energy Diversity and Security," A Tribute the work of Dr Shimon Awerbuch. Elsevier, Oxford, 1 edn., 2008.

I. Fortin, S. Fuss, J. Hlouskova, N. Khabarov, M. Obersteiner, J. Szolgayova, "An integrated CVaR and real options approach to investments in the energy sector," The Journal of Energy Markets, vol. 1, p.p. 61-85, 2008.

S. Fuss, D. J. A. Johansson, J. Szolgayova, M. Obersteiner, "Impact of climate policy uncertainty on the adoption of electricity generating technologies," Energy Policy, vol. 37, p.p. 733-743, 2009.

J. Hansen, Mki. Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson-Delmotte, M. Pagani, M. Raymo, D.L. Royer, and J.C. Zachos, "Target atmospheric CO_2: Where should humanity aim?" Open Atmos. Sci. J., vol. 2, p.p. 217-231, 2008.

International Energy Agency, "Climate Policy Uncertainty and Investment Risk," IEA/OECD: Paris, France, 2007.

International Energy Agency, "Projected Costs of Generating Electricity 2005 Update," OECD Nuclear Energy Agency, Paris, 2005.

International Institute of Applied Systems Analysis (IIASA), 2007. GGI Scenario Database, Laxenburg, Austria, available at http://www.iiasa.ac.at/Research/GGI/DB/.

P.S. Reinelt, D.W. Keith, "Carbon capture retrofits and the cost of regulatory uncertainty," Energy Journal vol. 28, p.p. 101-127, 2007.

R. Rockafellar, S. Uryasev, "Optimization of Conditional Value at Risk," Journal of Risk, vol.2, p.p. 21-42, 2000.

S. Uddin, L. Barreto, "Biomass-fired Cogeneration Systems with CO_2 Capture and Storage," Renewable Energy, vol.32, p.p. 1006-1019, 2007.

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Fuel price and technological uncertainty in a real options model for electricity planning

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ABSTRACT

Electricity generation is an important source of total CO_2 emissions, which in turn have been found to relate to an acceleration of global warming. Given that many OECD countries have to replace substantial portions of their electricity-generating capacity over the next 10–20 years, investment decisions today will determine the CO_2-intensity of the future energy mix. But by what type of power plants will old (mostly fossil-fuel-fired) capacity be replaced? Given that modern, less carbon-intensive technologies are still expensive but can be expected to undergo improvements due to technical change in the near future, they may become more attractive, especially if fossil fuel price volatility makes traditional technologies more risky. At the same time, technological progress is an inherently uncertain process itself. In this paper, we use a real options model with stochastic technical change and stochastic fossil fuel prices in order to investigate their impact on replacement investment decisions in the electricity sector. We find that the uncertainty associated with the technological progress of renewable energy technologies leads to a postponement of investment. Even the simultaneous inclusion of stochastic fossil fuel prices in the same model does not make renewable energy competitive compared to fossil-fuel-fired technology in the short run based on the data used. This implies that policymakers have to intervene if renewable energy is supposed to get diffused more quickly. Otherwise, old fossil-fuel-fired equipment will be refurbished or replaced by fossil-fuel-fired capacity again, which enforces the lock-in of the current system into unsustainable electricity generation.

1. Introduction

The plants installed in the near future will be used for the coming decades and contribute to cumulative emissions while combusting fossil fuels. This problem is relevant to both industrialized countries with rising replacement demand and developing and transition countries, where quickly rising energy demand propels the need for more generating capacity. The question that arises for the policy-maker then relates to the type of power plants by which the old (mostly coal-fired) capacity will be replaced. Will coal-fired power plant owners opt for coal-fired power plants again? Or will renewable energy be phased in, as old capacity is retired and fossil fuel prices rise and fluctuate? In addition to answering these questions, we are interested in the role of technical change. Can technological progress in less carbon-intensive generation technologies be a savior of last resort?

These considerations illustrate that electricity planning is surrounded by a number of uncertainties. As mentioned above, one source of uncertainty is the risk associated with the volatility of (growing) fuel prices, in the case of this study coal. Oil and gas prices fluctuate even more sharply. This can lead to considerable losses for the individual power producer, but also in terms of a country's GDP. Awerbuch and Sauter [1] present results that point to elasticities of GDP with respect to oil prices of about 10%. It is therefore important to understand how the volatility of fuel prices influences investment decisions.

The uncertainties involved in fuel price processes (usually accompanied by an upward trend) might lead to the conclusion that renewable, "zero-fuel-price" technologies might outperform the conventional power plants, in addition to their advantage of not emitting CO_2. However, the main disadvantage of such "green" technologies is their high fixed cost, which has so far inhibited the large-scale diffusion of renewable technologies in the electricity sector amongst other factors. Proponents of renewable energy have pointed to the fact that these costs are subject to major reductions as technological change progresses. To illustrate the vast scope for improvement, consider Fig. 1, which shows several renewable power technologies' projected change in overnight investment cost over the next decades based on a study by the European Commission [2].

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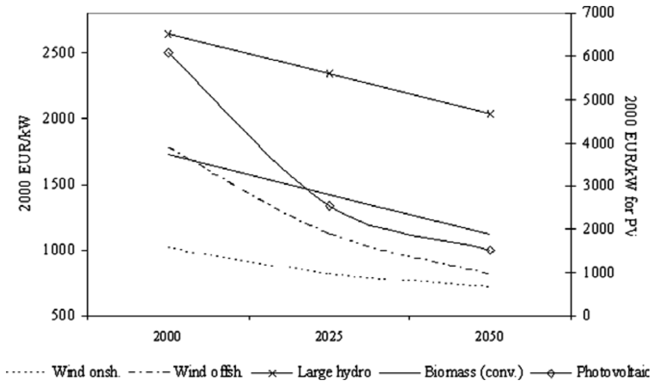

Fig. 1. Evolution of overnight investment cost of renewable power technologies (adapted from [2]).

Fig. 1 draws a very optimistic picture for future power investments. However, technological improvement itself is an inherently uncertain process, which needs to be taken into account when making investment decisions. Whether research really results in the projected cost reduction and at which point in time it would do so exactly, can never be determined with absolute certainty. Therefore, the arrival of cost-reducing innovations must be treated as a stochastic process. With respect to the technological prospects of established technologies, it can be said that most of them are already in a later stage of maturity than renewable technologies, which still have large scope for improvements that might also occur at a relatively fast pace initially. There are studies that indeed find evidence for this hypothesis. They look at so-called progress ratios (PR), which is the percentage of initial costs (per unit of output) that current costs will reach as a result of doubling their output (of installed capacity). It is found that gas turbines had a lower PR during their R&D phase than during their commercialization phase, i.e. costs were reduced by a lower percentage for each doubling of cumulative output than before (e.g. [3]). For comparison, Ref. [4] projects a relatively low PR for the capital costs of onshore wind generation – not reporting a precise number, but a range of PR projections. This indicates a large potential of wind energy in the future, but the wide range in the projections also points to the uncertainty associated with these promising rates of progress. However, while PRs account for the effects of learning-by-doing (i.e. improvements after installment), the nature of technical change in our framework is purely embodied, implying that new equipment has to be bought and installed in order to enjoy the benefits of the latest technological improvements. This is important because it creates further value to waiting, as technical change is exogenous. We have decided to analyze the effect of uncertainty in a real options framework, as this allows us to take into account that the capital invested into a specific power plant is sunk and the investment decision irreversible. Furthermore, real options models consider the flexibility of the investor to invest earlier or gain more information by postponing investment. The real options literature of primary interest for this study deals with uncertainty about technological change and input cost or revenue uncertainty, including [5–7]. Among these studies, only two deal with technological and revenue/input cost uncertainty simultaneously, however: both [8,9] derive analytical solutions for special cases.[1] In the model presented here, an analytical solution can generally not be obtained either, and we want to abstract from special cases, which do not seem to have realistic applications for our problem.

[1] In [8], the interest rate needs to be zero and fuel price uncertainty absent in order to find an analytical solution; [9] solves analytically for extreme cases only, such as the complete collapse of investment cost.

This model adds to the existing work in this field by formulating a more general framework than [8,9] and applying it to the case of investment in the electricity sector. To our knowledge, applications of real options theory to technological change in the electricity sector with derived climate change policy implications are rare, apart from attempts to capture learning effects by including learning curves into real options models.[2] However, such an approach to technological change does not take into account the embodiment of technological change that we want to incorporate. While Pindyck's [8] model provides useful implications and is straightforward, it is not suited for our purpose because it relies on sequential investments, where the project can be abandoned midstream. This explains the canceling of many nuclear power plants in the US in the early 1980s because of the large construction cost uncertainty at that time. However, we are interested in the situation when replacement investment is needed and thus midstream abandonment is not a relevant strategy in our case. Since we exclude this possibility, technological uncertainty has a much more profound effect in our model. Murto [9] models technical change with a Poisson process, in which we follow him closely, but he makes some assumptions that are not suitable for our problem. For example, he assumes that upon investment, the producer will receive a perpetual revenue stream, while in the case of power plants, the stream of profits ensuing investment is evidently limited by the lifetime of the plant. Furthermore, as mentioned before, we do not want to restrict ourselves to examine the timing of investment in a particular utility, but we want to focus on the switch or transition from an established (fossil fuel) power plant to one based on renewable energy under the described uncertainty.[3] If technological advance and the risks associated with stochastic fossil fuel prices do not result in earlier investment into renewables, policy makers have to provide another investment trigger.

The data used indeed suggest that a typical coal-fired power plant will only be scrapped in favor of a wind farm when an additional investment incentive (here CO_2 prices) is introduced. With increasing fuel prices and positive rates of technical change for the wind technology, a constant CO_2 price of 70 €/ton will trigger investment into a wind farm in the second half of the planning period. At current prices of CO_2 permits traded at EEX, this implies that today's CO_2 prices would need to quadruple to achieve a transition to renewables within the next 35 years.[4] At current prices the wind farm is only phased in when the coal-fired power plant's lifetime is over. Raising the price to 75 €/ton leads to much earlier discarding of the coal-fired plant. The wind farm would then already be adopted within the next 5 years. A study by [12] shows that depending on the development of carbon capture technologies for coal-fired power plants, rates of technical change of renewables, coal prices and market development, renewable energy (they use a mix of technologies) could become competitive within the next 15–45 years. They assume a CO_2 price level of 35 €/ ton. It is therefore up to the potential negotiators of a post-2012 carbon agreement to keep in mind that the market itself will not provide sufficient incentives for private investors to make a shift towards renewable energy in the absence of technological breakthroughs.

[2] Kumbaroğlu et al. [10] include learning curves for renewable energy into their real options model. They find that, for Turkey, the diffusion of renewable energy technologies will only occur if policies are directed to that cause because they suffer from high capital cost. On the other hand, active promotion of green technologies will accelerate learning and result in faster adoption of these technologies as costs decrease more quickly.

[3] We will first adopt a simple experimental setting with only one plant, which improves due to uncertain technical change, in order to distill the effects of technological progress itself (i.e. the rate).

[4] This does not seem to be far off the estimates of the IPCC, who suggest that a CO_2 price of $100/ton will be necessary to stabilize cumulative CO_2 emissions at levels associated with moderate global warming.

2. The real options model

The model that we develop here focuses on two power plants: a coal-fired power plant (representative of the fossil fuel technologies) and an offshore wind farm (representative of renewable energy technologies). The coal-fired power plant suffers from fluctuations in the price of coal. At the same time, it is a relatively mature technology in the sense that we do not expect further decreases in cost. The wind farm, on the other hand, has promising expected rates of technical change and is obviously not subject to fuel price volatility. However, even though the scope for technical change might be high, the realization of such progress is uncertain.[5]

We model technical change as a reduction in the investment cost of a wind farm normalized to provide the same amount of electricity as the coal-fired power plant. There are two ways to look at this. First, with the arrival of an innovation, investment costs are reduced by a specified percentage. The uncertainty here concerns the arrival rate: the higher the arrival rate, the more certain investors can be that an innovation will arrive within a relatively short period of time. On the other hand, with a certain arrival rate, the magnitude of the improvement is a source of uncertainty. If technical change is to be realized by frequent arrivals of innovations that improve costs only marginally, this might be preferable to a situation where very few innovations lead to huge drops in cost. Fixing the level of cumulative technical change and varying only the arrival rate or step size leading to this level provides a way to analyze uncertainty about technical change without confusing the effect with the result of changing the rate of technical change. Fuel price uncertainty is represented by letting the coal price follow a geometric Brownian motion.

2.1. Framework

Eq. (1) represents the change in the fuel price, p^f, where α is the drift parameter, σ^f is the volatility parameter and dz is the increment of a standard Wiener process.

$$\mathrm{d}p_t^f = \alpha \cdot p_t^f \mathrm{d}t + \sigma^f \cdot p_t^f \mathrm{d}z \tag{1}$$

The effect of uncertainty can then be investigated through the volatility parameter, σ_t^f. The expected value of p_t^f is $p_t^f \cdot e^{\alpha \cdot t}$. Technical change in the alternative technology is occurring in response to the arrival of innovations. This arrival follows a Poisson process according to [9]. Let us denote the investment cost by C_t evolving according to:

$$C_t = C_0 \cdot \xi^{W_t} \tag{2}$$

In (2), W_t is a Poisson random variable, with an average arrival rate (of innovations) of λ. $0 \leqslant \xi \leqslant 1$ determines the size of the step or – in other words – the magnitude of the technological improvement achieved through the innovation. The expected value of C_t is therefore $C_0 \cdot e^{-\lambda \cdot t \cdot (1-\xi)}$ as $\lambda \cdot t$ counts the number of innovations. Note that only if $\lambda(1-\xi)$ remains constant, the expected path of technological progress is unchanged. Eq. (3) shows the variance of the investment cost (see also [9], p. 1480):

$$Var(C_t) = C_0^2 \cdot ((e^{-\lambda(1-\xi)t})^{1+\xi} - (e^{-\lambda(1-\xi)t})^2) \tag{3}$$

The implication from (3) is that a decrease in λ and ξ (so that $\lambda(1-\xi)$ remains constant) increases the variance of costs, while an increase in the parameters decreases the variance until the point where the cost is reduced to zero by the very first innovation. Murto [9] considers this polar case along with some other simplifications because it allows him to derive an analytical solution. However, we do not regard this to be a realistic scenario for our application and want to focus on cases, where the cost is reduced according to general expectations for the corresponding technologies.

Immediate profits are composed of the revenues from selling electricity, $p_e \cdot q_e$, and the revenues from providing heat, $p_h \cdot q_h$, both of which are constant over the planning period.[6] Fuel costs, $p_f \cdot q_f$, are subtracted. Other costs involve the outlays for operations and maintenance, *OMC*, which are fixed for the amount of electricity that is generated per year, and the CO_2 taxes or expenses for the purchase of permits. Finally, the costs of the action taken by the investor at time *t* need to be considered: these are zero in case no investment is made and equal to the cost of installing new capacity if the investment option is exercised. Note that these costs depend on the advance of technical change and the uncertainty associated with this:

$$\pi(m_t, a_t, p_t^f, CC_t) = q_e(m_t) \cdot p_t^e + q_h(m_t) \cdot p_t^h - q_f(m_t) \cdot p_t^f - q_c(m_t) \cdot p_t^c - OMC(m_t) - CC_t(a_t, \lambda, \xi) \tag{4}$$

where m_t is the state the investor is currently in. In Section 3.1 this is either a situation where there is no plant or where the wind farm has been deployed. In Section 3.2 this is a setting where a coal-fired power plant already exists. At a later stage it can be a state where a new coal-fired power plant has replaced the old one or where a wind farm has been built instead (see Table 1). CC_t is equal to C_t in Eq. (2) when an investment is made ($a_t = 1$) and equal to zero when the option is not exercised ($a_t = 0$).

The investor's problem can be formulated as an optimal control problem and restated in a recursive functional form, so that we can use dynamic programming to determine the optimal action. This means that we screen all possible values of the value function depending on all the possible states that the decision-maker can be in depending upon all realizations of prices and technical change and thereby determine the optimal action in each stage for all these cases. Mathematically, we formulate a value function in Eq. (5), which has to be maximized by determining the optimal investment strategy $\{a_t\}_{t=1}^T$, where *T* is the planning horizon.

$$V(t, p_t^f, CC_t) = \max_{a_t \in A(m_t)} \{\pi_t(m_t, a_t, p_t^f, CC_t) + e^{-\gamma \cdot \Delta t} E(V(t + \Delta t, p_{t+\Delta t}^f, CC_{t+\Delta t}) \big| m_t, p_t^f, CC_t)\} \tag{5}$$

where γ is the discount rate and $a_t \in A(m_t)$ is an action in the set of all actions. The value function has a straightforward interpretation. The first part is the immediate profit, $\pi_t(m_t, a_t, p_t^f, CC_t)$, which the producer receives upon investment. The second part, $\{e^{-\gamma \cdot \Delta t} E(V(t + \Delta t, p_{t+\Delta t}^f, CC_{t+\Delta t}) \big| m_t, p_t^f, CC_t)\}$ represents the discounted expected continuation value. This term is evaluated for the specific state the producer is in, which changes as actions are undertaken. For example, at the end of the lifetime of the coal-fired power plant the wind farm could replace the coal-fired power plant. Then fuel costs would drop to zero. However, it could also be that the coal-fired technology is still cheaper than the wind farm. In this case the investor would build another coal-fired power plant to replace the expired one and thus make no transition towards renewables.

[5] Wind also suffers from a low capacity factor and is therefore not a reliable candidate for providing large-scale base loads. Although we account for the capacity factor, we abstract from the distinction between peak and base load provision here: wind is a technology representative of all renewable energy carriers, chosen for illustrative purposes and not to claim that the electricity sector should exclusively rely on wind.

[6] We have chosen to assume that the byproduct heat can be sold because these revenues represent a further advantage over renewable energy technologies that do not have this extra source of revenue. Renewables therefore need to overcome an even higher barrier than "only" their high investment and O&M cost.

Table 1
Experimental settings in Sections 3.1 and 3.2.

	$m_t = 0$	$m_t = 1$	$m_t = 2$
Setting Section 3.1	Nothing built	Wind farm has been built	–
Setting Section 3.2	Coal-fired plant operational	Wind farm has replaced coal-fired plant	Wind farm not adopted (new coal-fired plant after 40 years)

Table 2
Power plant data for coal and wind from [11].

Parameters	IGCC coal	Offshore wind
Electricity output (TWh/yr)	3285	3285
CO_2 emissions (kt CO_2/yr)	2155	0
Fuel consumption (TJ/yr)	23,188	0
Fuel cost (€/TJ)	1970	0
O&M fixed cost (1000 €/yr)	40,250	49,392
Effective installed capacity (MW)	500	833.33
Capacity factor (%)	75	45
Heat efficiency (%)	34	0
Heat price (e/TJ)	11,347	
Investment cost (1000 €)	686,500	10,49,358
Lifetime (years)	40	25

$E(V(\cdot))$ can be numerically computed in three different ways: the first one involves partial differential equations, the second uses binomial lattices and the third (which we choose) is Monte Carlo simulation (see [13] for a detailed description of the method).

2.2. Coal and wind plant data

The first technology is an IGCC (Integrated Gasification Combined Cycle) plant with an integrated module capturing and storing a portion of its CO_2 emissions. Since we want to focus on the effects of fuel price and technological uncertainty and not on CO_2 prices as the main trigger for a transition in the first instance, we will first keep CO_2 prices low. The other technology is an offshore wind farm. It is considerably more expensive than coal in terms of capital and O&M costs and also its low capacity factor is a disadvantage (see Table 2).

3. The results

The analysis of investment sensitivity to uncertainty about fuel prices and technological improvements is divided into two experiments (see Table 1). First, we want to focus exclusively on technological uncertainty. The experiment that we have designed for this purpose therefore presents only one investment option, namely to invest into the wind farm. We first start out by investigating the effects of different rates of technological progress on the timing of investment. Varying the degree of uncertainty by adjusting λ and ξ correspondingly (see Eq. (3)), we can analyze how the investor reacts to these changes. The setting of the second experiment is such that we consider an established coal plant,[7] which has no prospect of cost reductions due to technological improvements. Furthermore, the price of coal is stochastic and (slightly) rising (see Eq. (1)). The analysis will then determine how the optimal date of replacing existing capacity with the wind farm responds to changes in fuel price and technological uncertainty. If the wind farm is not competitive, the coal-fired plant will be kept until it expires and will then be replaced by another IGCC plant.

3.1. Technological change and uncertainty

Let us first analyze the impact of different rates of technical change on the timing of investment and interpret it in terms of plant and option value. In Fig. 2 the plant and investment option values for a modest rate of technical change ($\lambda(1-\xi) = 0.2\%$) and for a relatively higher rate ($\lambda(1-\xi) = 0.5\%$) are plotted. Uncertainty is kept low by setting $\lambda = 1$ in order to avoid cross-effects.

The investor will exercise the option to install the plant, as soon as the plant value (i.e. the value of the immediate profits that accrue upon investment) exceeds the option value of waiting. This is the case around year 11 for the low rate of technical change, i.e. where the solid circles and triangles meet. For higher technological progress, the plant and also the option to invest into the plant reach a much higher level as shown by the transparent circles (option value) and triangles (plant value). In addition, the option value rises more sharply relative to the plant value. This can be explained by the fact that technological improvements are embodied in the latest capacity; once investment has taken place, no further cost reductions can occur. Therefore, if a larger decrease in costs can be expected at the same level of certainty, it pays off to wait longer and reap the benefits of ongoing technological change.

We now turn to the analysis of uncertainty and use the results obtained above for $\lambda(1-\xi) = 0.5\%$ and $\lambda = 1$ as a reference scenario. As already pointed out, a relatively high λ lowers uncertainty about future technological advances with respect to investment cost. The high number of innovations that arrive over the planning horizon is compensated by a relatively smaller step size. More specifically, ξ will be 99.5%, which means that costs fall by only 0.5% each time a new innovation is found. If we have a planning horizon of 50 years, there will in total be 50 innovations, i.e. there will be a fall of 25% in investment costs over 50 years, which is not unrealistic looking back at the projections displayed in Fig. 2.

To model larger uncertainty, we fix $\lambda(1-\xi)$ at 0.005, and choose $\lambda = 0.1$ for the beginning. This gives us a step size of $\xi = 95\%$. With such a low λ, this is a situation of great uncertainty, since the investor cannot be sure when the innovations will exactly arrive. Since the cost reductions are quite substantial, waiting for them gets

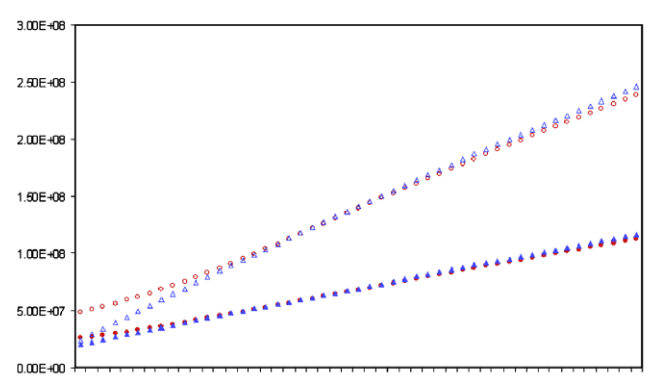

Fig. 2. Option values (circles) and plant values (triangles) for low (solid) rate of technical change (TC) and high (transparent) rate of technical change in (€).

[7] Coal-fired plants are always preferred over wind in the beginning because of their current cost advantage.

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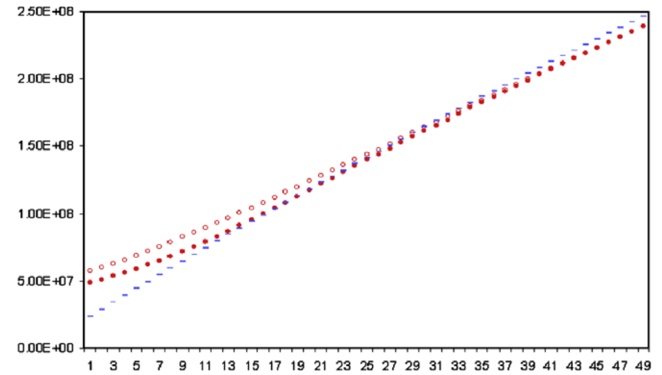

Fig. 3. Option values (circles) and plant values (steps) for high uncertainty (transparent circles) and low uncertainty (solid circles) in (€).

more valuable. The outcome of this simulation[8] is that, on average, the wind farm is built after year 26. As we can see in Fig. 3, the option value is higher with more technological uncertainty, while the plant value is largely unaffected. This is the reason why investment occurs later than in the lower uncertainty case. The analysis implies that we find a negative relationship between investment and uncertainty, as is typical in the real options literature: the higher the variance, the later the investment option is exercised.

The intuition is that, if the expected decrease in costs over a specific time horizon is quite substantial, but the investor cannot be sure how late it will be realized, it will pay off to wait for that improvement to materialize because the profits that accrue thereafter are higher and more than compensate for the costs of waiting. On the other hand, if the investor knows that a lot of innovations will arrive during the planning horizon, he can be sure that at least some of them will arrive in the beginning of the planning period and that he does not forgo much by investing relatively early.

3.2. Technological change and fuel price uncertainty

What real options models typically find for input cost uncertainty is that higher uncertainty (modeled by increasing the volatility parameter) leads to a postponement of investment because higher volatility leads to a higher option value of waiting. In our setting, this is much more complicated, since the option value is composed not only of waiting and keeping the profit flows from having the coal plant operational. At the same time, the wind farm's overnight investment costs are reduced due to ongoing (exogenous) technological progress, which creates additional value to waiting.

To illustrate this, we have left the fuel prices at a constant level in the first experiment. In Fig. 4 the option value is therefore clearly upward-sloping, since the only reason why there actually is an option value (given that fuel prices are constant) is that there is ongoing technical change benefiting the wind farm. And since the benefits of technical change are embodied in the latest version of the plant only, the gain from waiting is positive and increasing. Another important remark that has to be made about Fig. 4 is that without a price on CO_2, the option value line would be enormously far removed from the plant value line, and investment would never occur. Only a CO_2 tax (or permit price) leads to eventual adoption of the wind farm. The upper option value line corresponds to a CO_2 price of 70 €/ton, while increasing this price by 5 € depresses the option value and leads to earlier adoption of the wind farm. From the policy-maker's perspective, this implies that the cost disadvantages of renewable energy (here wind power) will not be overcome

[8] The number of simulated technology paths is 10,000.

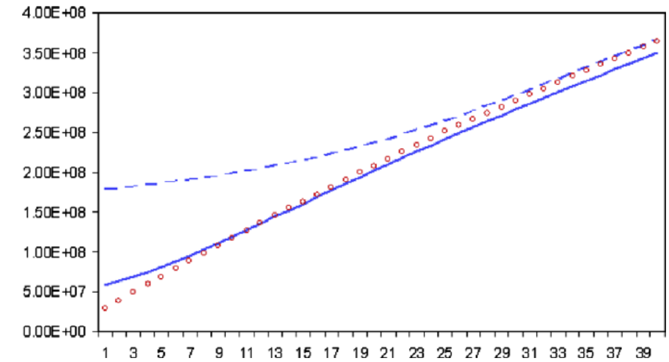

Fig. 4. Plant value (circles) and option values (lines) for low (dashed line) and high (solid line) CO_2 prices in (€).

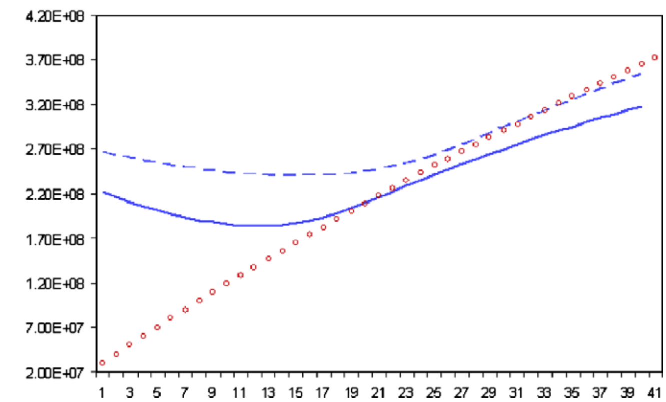

Fig. 5. Plant value (circles) and option values (lines) for slowly (dashed line) and rapidly (solid line) rising fuel prices in (€).

by technological advance in the short run according to current projections.

Adding rising fuel prices, which rise deterministically in the next experiment, Fig. 5 demonstrates that the option value is influenced by two forces – the rising fuel price, which decreases the option value of keeping the coal-fired plant operational and brings the option value closer to the wind farm's plant value, and the option value of waiting for more technological improvement to materialize, so that less has to be spent to set the wind farm up. In the beginning of the planning horizon, the first effect more than outweighs the second influence and the option value line slopes downward. Only later, the increase in the value of waiting for further cost reductions starts to exceed the decrease in the value of keeping the coal-fired power plant. Furthermore, the difference between the dashed line and the solid line in Fig. 5 demonstrates that the option value is shifted downwards when coal prices rise more quickly. Investment is therefore brought forward in time, consistent with expectations.

Now we can finally turn to the full experimental setting with rising and stochastic coal prices, as described in Eq. (1). In Fig. 6 the crosses refer to the option value with stochastic coal prices.[9] We observe that with stochastically rising prices, the option value is shifted slightly upwards. However, the option value converges back to the level of the "deterministic" option value after the "waiting for more technical change"-value starts to exceed the falling option value of keeping the coal plant. This is because the fluctuations in the coal price have no effect on that part of the option value. The

[9] We have inflated σ^f by a factor of 10 in this experiment, since the low volatility of coal made no visible difference in the graph.

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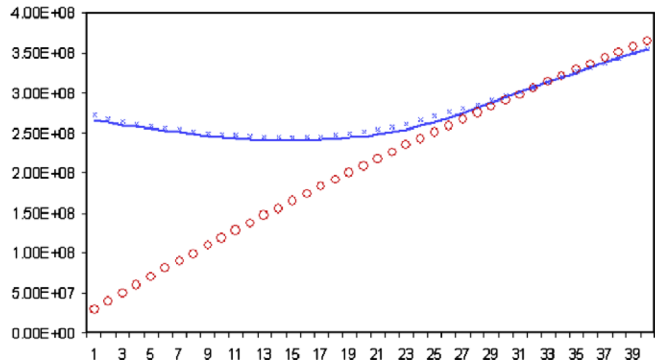

Fig. 6. Plant value (circles) and option values (lines) for deterministic (line) and stochastic (crosses) fuel prices in (€).

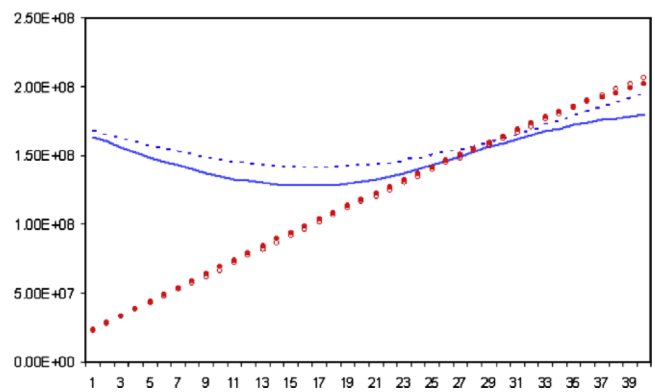

Fig. 7. Technological uncertainty: plant values with less uncertainty (filled circles) and higher uncertainty (transparent circles) and option values (lines) for lower (solid line) and higher (dashed line) uncertainty in (€).

average investment threshold therefore remains unchanged in this experiment. However, if policy makers trust in fuel price uncertainty to provide sufficient incentives for investors in the electricity sector to retire fossil-fuel-based capacity in favor of renewable energy, these results provide no support for such hypotheses. Even if we would exclude the possibility of technological improvements in wind, which leads to the convergence of the two option value lines in Fig. 6, the net effect would not deviate much from the average. If anything at all, it would lead to a postponement of investment. In our setting, where the wind farm is only phased in towards the end of the planning period, this could imply that there is no transition to renewable energy at all.

Finally, we want to examine the difference that technological uncertainty with respect to the investment cost of the wind farm makes in the full setting. Fig. 7 below shows the plant values and option values for a λ of 0.1 and 0.8, respectively.

The former case corresponds to a situation where arrivals occur only sporadically but reduce costs a lot, while a λ of 0.8 stands for more continuous, but also less drastic improvements.[10] Note that both values for λ ultimately lead to the same plant value, only the line for the plant value with $\lambda = 0.1$ evolves more erratically than the one with $\lambda = 0.8$. The option value is influenced much more heavily by the change in technological uncertainty, however. As could be expected from our analysis in Section 3.1, the option value with higher uncertainty (dashed line) is above the one with lower uncertainty (solid line) in Fig. 7. This leads to a postponement in the adoption of the wind farm by approximately 5 years in this case.

4. Conclusion

This paper has presented a real options model with stochastic fuel prices and stochastic technical change in the electricity sector to explore the effects of uncertainty on the behavior of investors. As some authors have pointed out (e.g. [1]), volatile fuel prices might cost economies more than generally expected. It appears that renewable energy carriers, which come at a zero "fuel" cost, such as wind, have a large advantage over fossil fuel technologies in this respect. Furthermore, even though they might still be expensive in terms of their capital and O&M costs, renewables have bright prospects in terms of their technological improvement over the next decades [2]. At the same time, renewables do not generate CO_2, which implies that a transition to their use is desirable from an environmental point of view. An early adoption of renewable energy will assist most governments' striving for sustainable energy development.

However, it stands to question whether the combination of rising, uncertain fuel prices and technological advance in the area of renewables will really provide sufficient incentives for investors to switch from an established fossil fuel plant (here coal) to a renewable technology (here wind). The application of our model to recent data from [11] suggests that this may not be the case. Without an additional trigger (here CO_2 prices), the transition is not profitable for the investor in the short run, even if the rate of technical change had been higher. Furthermore, the analysis of the effect that uncertainty has on the investment pattern suggests that uncertainty about fuel prices does not have a significant effect on the timing of renewable energy phase-in. If anything at all, the price fluctuations will lead to a slightly higher option value, as long as this option value is dominated by the value of keeping the coal-fired plant operational. As soon as the value of waiting for more technical change to materialize dominates the option value, fuel price volatility will no longer play a role for the optimal investment date.

Including technological uncertainty complicates matters further: if we abstract from the effect that rising (and possibly stochastic) fuel prices have on the option value of waiting to install the wind farm, larger uncertainty will raise the option value of waiting as illustrated in Fig. 3 and therefore lead the investor to postpone the adoption of the wind farm. This is because technological progress is modeled to be embodied in the latest version of capacity. Therefore, if the investor can expect a relatively large fall in the cost of installing the wind farm, it will pay off to postpone the decision for a while and wait for that big cost drop to occur. Changing the setting, so that we either keep an existing coal-fired plant or replace it with a wind farm (before or after expiration) or another coal plant (after expiration), adds another influence on the option value of waiting. More precisely, the rising fuel prices reduce the value of keeping the coal-fired power plant. If we would not include the value of waiting for more technological progress to improve the costs of the wind farm, the option value lines in Figs. 5 and 6 would cross the plant value line much earlier and trigger investment already in year seven. However, the value of waiting for the benefits of technical change raises the option value and even starts to dominate the development of the option value later during the planning period, so that the option value slopes upward and adoption occurs later than if we had not taken the waiting benefits into account.

With respect to technological uncertainty in the presence of coal-fired capacity, which looses attractiveness as fuel prices rise,

[10] We have chosen a price of 70 €/t CO_2 again, with $\lambda(1-\xi)$ at 0.005.

we also find a "typical" real options result. In particular, we find a negative uncertainty–investment relationship again: when the investor can be sure that innovations will arrive within the next few years to reduce the investment cost, the investment option is exercised earlier than if there is uncertainty, which increases the option value of waiting.

Finally, a few words need to be said about the limits of the analysis presented: the exogeneity of technical change is a simplification because progress is endogenous insofar that the R&D needed to drive the progress must be financed. In the ideal framework, the private investor would value an R&D option to further develop immature technologies in the presence of the option to make a transition to that same technology – thus taking into account that also the arrival of an innovation needs to be paid for.

Acknowledgement

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References

[1] Awerbuch S, Sauter R. Exploiting the oil-GDP effect to support renewables deployment. Energy Policy 2006;34:2805–19.
[2] European Commission. World Energy Technology Outlook: WETO H2; 2006. <http://ec.europa.eu/research/energy/pdf/weto-h2-en.pdf>.
[3] Oxera Consulting Ltd. What is the potential for commercially viable renewable generation technologies? Report, prepared for the Department of Trade and Industry, London; 2005.
[4] European Wind Energy Association. Wind energy: the facts – an analysis of wind energy in the EU-25. Report, EWEA; 2004.
[5] Balcer Y, Lippman S. Technological expectations and adoption of improved technology. J Econom Theory 1984;84(2):292–318.
[6] Grenadier S, Weiss A. Investment in technological innovations: an option pricing approach. J Financ Econom 1997;44:397–416.
[7] Farzin Y, Huisman K, Kort P. Optimal timing of technology adoption. J Econom Dynam Control 1998;22:779–99.
[8] Pindyck R. Investments of uncertain cost. J Financ Econom 1993;34:53–76.
[9] Murto P. Timing of investment under technological and revenue-related uncertainties. J Econom Dynam Control 2007;31:1473–97.
[10] Kumbaroğlu G, Madlener R, Demirel M. A real options evaluation model for the diffusion prospects of new renewable power generation technologies. Working paper no. 35. Centre for Energy Policy and Economics Working Papers, Zurich; 2004.
[11] International Energy Agency. Projected costs of generating electricity (2005 update). Paris: OECD/IEA; 2005.
[12] Viebahn P, Nitsch J, Fischedick M, Esken A, Schüwer D, Supersberger N. Comparison of carbon capture and storage with renewable energies technologies regarding structural, economic, and ecological aspects in Germany. Int J Greenhouse Gas Control 2007;1(1):121–33.
[13] Fuss S, Szolgayová J, Obersteiner M, Gusti M. Investment under market and climate policy uncertainty. Appl Energy 2008;85:708–21.

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Int. J. Energy Res. 2008; **32**:1080–1091
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Optimal location of wood gasification plants for methanol production with heat recovery

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SUMMARY

Second generation biofuels from wood gasification are thought to become competitive in the face of effective climate and energy security policies. Cost competitiveness crucially depends on the optimization of the entire supply chain—field-wheel involving optimal location, scaling and logistics.

In this study, a linear mixed integer programming model has been developed to determine the optimal geographic locations and sizes of methanol plants and gas stations in Austria. Optimal locations and sizes are found by the minimization of costs with respect to biomass and methanol production and transport, investments for the production plants and the gas stations. Hence, the model covers competition in all levels of a biofuel production chain including supply of biomass, biofuel and heat, and demand for bio- and fossil fuels.

The results show that Austria could be self-sufficient in the production of methanol for biofuels like M5, M10 or M20, using up to 8% of the arable land share. The plants are optimally located close to the potential supply of biomass (i.e. poplar) in Eastern Austria, and produce methanol around 0.4 €$\,l^{-1}$. Moreover, heat production could lower the methanol cost by 12%. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: biofuel for vehicles; gasification; heat recovery; facility location; mixed integer programming; fossil fuel

1. INTRODUCTION

1.1. Background

The European energy policy is increasingly driven by considerations of climate change impacts and energy security issues. Therefore, the European Council has proposed that 15% of total energy consumption should be produced from renewable resources in 2015; for the European Parliament the share of renewable resources on total energy consumption should be even 25% in 2020. However, the EU-25 share of renewable resources on gross domestic energy consumption was about 6.3% in 2004 [1]. Consequently, the

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European Commission has published a renewable energy road map that supports an obligatory share of 20% in 2020. The road map emphasizes the importance of a regulatory and legal framework to encourage investments and outlines several measures that help to reach this target level [2]. So far, substantial progress in renewable energy has been made only in the electricity sector; the transport and the heat/cooling sectors are lagging behind their intermediate targets. Particularly, biofuels will need additional support to attain the EU target of 10% on total gasoline and diesel consumption in 2020. In 2007 all Member States were required to report national target levels of biofuels for 2010. Austria is currently aiming at a 10%-target level for biofuels in 2010 and one at 20% in 2020. In this study we investigate the potential of the realizations of these target levels, by analyzing a national methanol production chain for Austria.

1.2. Research objective

The energy chain of methanol production—harvesting, biomass transport, methanol production, methanol transport, methanol distribution—is analyzed (Figure 1). The cost of methanol is calculated and compared with one of the possible by-products, heat. The competition with fossil fuel is also taken into account as a competitor to biofuel.

In this study, the optimal geographical locations of the plants in Austria are determined by a mixed integer linear programming model [3]. The plants produce methanol and heat. The model minimizes the total costs of the energy chain described below by considering regional biomass supply, biomass production costs and demography in Austria.

Figure 1. Methanol energy chain.

2. METHODOLOGY

2.1. The methanol production chain

2.1.1. Biomass supply. Biomass production of a short-rotational poplar coppice system has been modeled by Schmid *et al.* [4] using the latest version of the bio-physical process model EPIC[†] [5]. The poplar coppice system is fertilized with nitrogen only in the first 2 years of each rotation period. Biomass is harvested every 6 years over a simulation period of 30 years. It is assumed that poplar coppice can only be planted on agricultural lands with decent slopes ($<5\%$) to keep harvesting costs low. Biomass production costs typically depend on the choice of biomass crops, management system, land type or basic climate conditions. In this paper we do not use a biomass costing calculator but rather assumed, for reasons of comparability, a regional biomass price of $30\,€\,\mathrm{m}^{-3}$ including extraction and pretreatment.

2.1.2. Biomass transportation. The biomass transportation cost (in $€\,\mathrm{TJ}^{-1}$) is described by Börjesson and Gustavson [6], and is represented by Equations (1) and (2), for truck transportations and tractor-trailer, respectively:

$$C_{\mathrm{Truck}} = 344 + 7.77d \tag{1}$$

$$C_{\mathrm{Tractor}} = 226 + 12.78d \tag{2}$$

The actual distance (in km) to the methanol plant, d, is defined as the direct distance multiplied by the estimated ratio of actual road length to direct distance. These values correspond to the transportation costs if the biomass is extracted from the surrounding areas.

2.1.3. Methanol production. Methanol can be produced from biomass via different gasification technologies. The methanol production facilities typically consist of the following steps: pretreatment, gasification, gas cleaning, reforming of higher hydrocarbons, shift to obtain appropriate H_2:CO ratios and gas separation for methanol synthesis and purification [7]. A gas

[†]The EPIC model version EPIC3060 with the program code from 02/03/2006 is used for this analysis.

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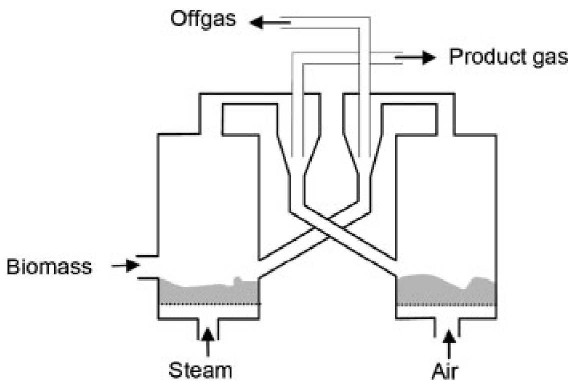

Figure 2. The indirectly heated, twin bed gasifier of Battelle Columbus Laboratory.

turbine or boiler is optional to employ the unconverted gas equipments for heat production (or a steam turbine for electricity co-production).

According to Hamelinck and Faaij [7], only circulating fluidized bed gasifiers are suitable for large-scale fuel gas production. This conclusion is based on an analysis of throughput, cost, complexity and efficiency issues. Hamelinck and Faaij analyzed two gasifiers for methanol production: a pressurized direct oxygen fired gasifier and an atmospheric indirectly fired gasifier. In this paper an atmospheric indirectly fired gasifier of Battelle Columbus Laboratory [8] type is used. This gasifier is indirectly heated by a heat transfer mechanism as shown in Figure 2. Ash, char and sand are entrained in the product gas, separated using a cyclone and sent to a second bed where the char is burned in air to reheat the sand. The heat is transferred between the two beds by circulating the hot sand back to the gasification bed. This allows one to provide heat by burning some of the feed, but without the need to use oxygen because combustion and gasification occur in separate vessels. The gasifier is fired by air and there is no risk of nitrogen dilution or need for oxygen production. Figure 3 presents the production chain of methanol [7].

The investment costs for different units of the base methanol plant (430 $MW_{biomass}$) are listed in Table I. Scale effects strongly influence the unit cost per plant capacity, which decrease with larger plants or equipments (such as boilers, turbines, etc.). For example, a methanol plant of 100 MW can be expected to be cheaper per GJ of methanol produced than a 10 MW plant, even though both plants are based on the same technology. This difference can be adjusted using the scaling function:

$$\frac{\mathrm{Cost}_a}{\mathrm{Cost}_b} = \left(\frac{\mathrm{Size}_a}{\mathrm{Size}_b}\right)^R \tag{3}$$

where R is the scaling factor, Cost_a and Cost_b are the costs of equipments for the biofuel plants (a) and (b), respectively, and Size_a and Size_b are the sizes of the biofuel plants (a) and (b), respectively. Using this information it is possible to calculate costs for different processing steps of methanol plants with different sizes. By adding investment costs from the separate units, the total investment cost for the new size is determined, and production cost for the current methanol plant size can be calculated. For biomass systems, R is usually between 0.6 and 0.8 [7]. The uncertainty range of such estimates is up to $\pm 30\%$ [7]. Table I lists the scaling factors based on a 430 $MW_{biomass}$ methanol plant.

The total capital requirement (TCR) for a process plant can be calculated from the process plant costs, as listed in Table II. The TCR provides an annual cost (AC) that is calculated using the following equation:

$$\mathrm{AC} = \frac{\mathrm{IR}}{1 - 1/(1+\mathrm{IR})^{t_e}} \mathrm{TCR} \tag{4}$$

where IR is the interest rate and t_e the economical lifetime or pay down period. The annual operating and maintenance costs are calculated as the sum of the elements listed in Table III. In this study the production of heat as a by-product is considered.

2.1.4. Methanol transportation. Depending on the quantity, infrastructure and distance, methanol can be transported by truck, train or ship. The costs of methanol transportation are calculated using figures from Börjesson and Gustavson [6]. The transportation cost by truck (in € $TJ^{-1}_{methanol}$) is a function of actual transportation distance, d, (in km):

$$C_{\mathrm{Truck}} = 138 + 3.05d \tag{5}$$

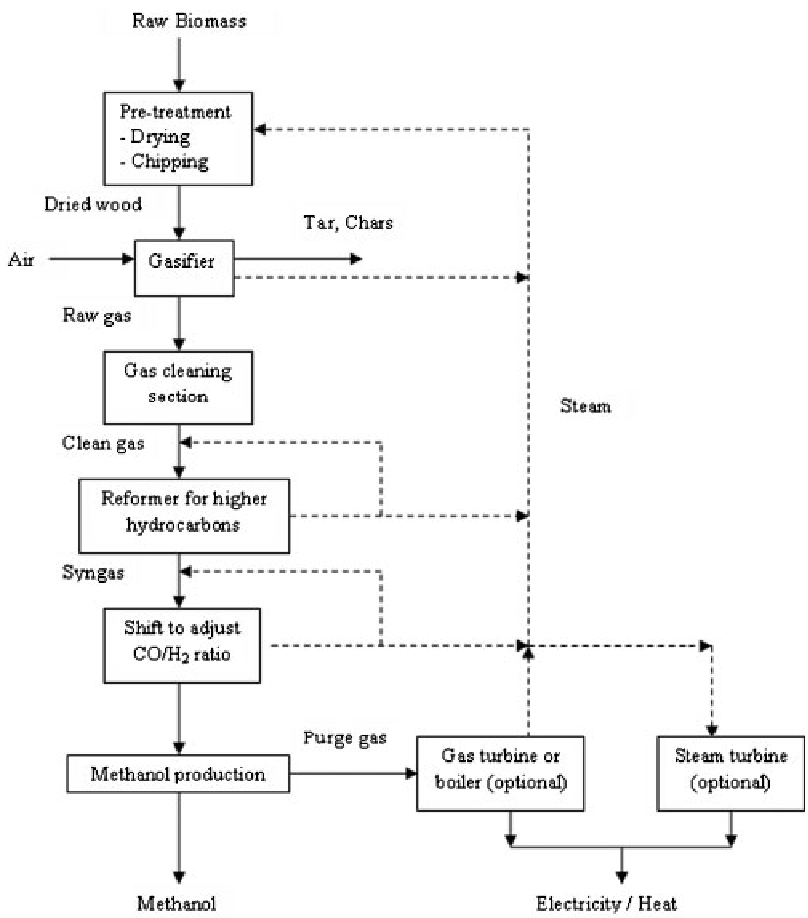

Figure 3. Process flow diagram of methanol production.

Table I. Base scale factors for a 430 $MW_{biomass}$ methanol plant [7].

Gasification system	R	Cost (M€)
Total pretreatment	0.79	31.4
Gasifier	0.65	25
Tar cracker	0.7	7.6
Cyclones	0.7	5.6
Heat exchanger	0.6	9.2
Baghouse filter	0.65	3.4
Condensing scrubber	0.7	5.6
Compressor	0.85	13.9
Steam reformer	0.6	37.8
Make-up compressor	0.7	14.3
Liquid phase methanol	0.72	3.6
Recycle compressor	0.7	0.3
Refining	0.7	15.7
Process plant cost (PPC)		173.4

The calculated cost might differ from the actual transportation cost, as the cost may be reduced due to discounts or special agreements [6]. In the calculations for transportation cost, these costs are scale-independent.

2.1.5. Methanol distribution. It is assumed that all the gas stations that are considered are able to distribute methanol. As methanol today is not widely used in the transportation sector, changes to gas stations would be required. One can consider a station that has three underground storage tanks of three grades of gasoline, two pump islands and four dispensers capable of refueling eight vehicles simultaneously. At an average fill-up of 51 l requiring 6 min, a station

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Table II. Total capital requirement for a process plant [9,10].

Capital required	Description
Total plant cost (TPC)	
Engineering fee	10% of PPC
Process contingency	2.345% of PPC
General plant facilities	10% of PPC
Project contingency	15% of (PPC+general plant facilities)
Total plant investment (TPI)	
Adjustment for interest and inflation	0.34% of PPC
Total capital requirement (TCR)	
Prepaid royalties	0.5% of PPC
Start-up costs	2.7% of TPI
Spare parts	0.5% of TPC
Working capital	3% of TPI
Land, 200 acres	200 acres at 6500 € Acre^{-1}

Table III. Annual operating and maintenance costs [9,10].

Operating and maintenance (O&M)	Description
Wood	30 € m^{-3}
Operator labor	3% of TPI
Supervision and clerical labor	30% of O&M labor
Maintenance costs	2.2% of TPC
Insurance and local taxes	2% of TPC
Operating royalties	1% of wood cost
Miscellaneous operating costs	10% of O&M labor

such as the one illustrated may service between 200 and 400 vehicles per day and have a gasoline throughput of 321 760–643 520 l month^{-1} [11]. Two scenarios can be analyzed, one is to add a methanol capacity to an existing station, and the second one is to consider that methanol would displace a fraction of existing gasoline storage capacity.

The costs for handling a gas station of methanol with a capacity of 124 918 l month^{-1} are between 0.2031 and 0.2412 € GJ$^{-1}_{\text{methanol}}$ regarding the chosen scenario. The costs are assumed to be independent of the methanol plant size [11].

2.2. Model

This section formulates the problem as a facility location problem (FLP). Solving the problem will result in the optimal locations and sizes of the plants and gas stations. The model is defined as a mixed integer linear optimization problem. To simplify the presentation, the defined model considers one time period (year), but it can easily be generalized to be multi-periodic.

The parameter S is the number of biomass supply regions, P is the number of plants, G is the number of gas stations and D is the number of demand regions. The corresponding sets are: $\tilde{S} = \{1, \ldots, S\}$, $\tilde{P} = \{1, \ldots, P\}$, $\tilde{G} = \{1, \ldots, G\}$ and $\tilde{D} = \{1, \ldots, D\}$. Besides biofuel, a plant may be constructed to produce one or several additional commodities. Let C be the number of additional commodities and define $\tilde{C} = \{1, \ldots, C\}$ as the corresponding set. Heat is the only commodity considered in this study.

The following variables are defined: $b_{i,j}$ is the amount of biomass delivered from supply region i to plant j, $x^{\text{biofuel}}_{j,k}$ is the amount of biofuel delivered from plant j to gas station k and $x^{\text{biofuel}}_{k,l}$ is the amount of biofuel sold at gas station k to costumers from demand region l. The variable x^c_j represents the amount of commodity c that is produced at plant j. Heat is then a so-called by-product. The variable x^{fossil}_l is the amount of fossil fuel sold to costumers from demand region l. The variables $b_{i,j}$, $x^{\text{biofuel}}_{j,k}$, $x^{\text{biofuel}}_{k,l}$, x^c_j and x^{fossil}_l are non-negative. The binary variables u_j and u_k, respectively, indicate whether the plant j and the gas station k are in operation. If u_j (u_k) is equal to one, then the plant (station) is in operation, otherwise u_j (u_k) is zero.

The cost for producing biomass in supply region i is c_i. The biomass delivered from region i is restricted by

$$\sum_{j=1}^{P} b_{i,j} \leqslant \bar{b}_i, \quad i \in \tilde{S} \tag{6}$$

where $\bar{b}_i$ is the available biomass (defined here as a certain percentage of all available biomass in Austria). The cost for transporting biomass from supply region i to plant j is $t_{i,j}$.

Plant j is described by the following parameters and equations. The cost for building a plant with maximal biofuel capacity $\bar{x}^{\text{biofuel}}_j$ is e_j and the cost for producing in the plant is c_j. The biofuel

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production is thus restricted by

$$\sum_{k=1}^{G} x_{j,k}^{\text{biofuel}} \leqslant \bar{x}_j^{\text{biofuel}} u_j, \quad j \in \tilde{P} \tag{7}$$

The efficiency of producing methanol is a_j^{biofuel} giving

$$a_j^{\text{biofuel}} \sum_{i=1}^{S} b_{i,j} = \sum_{k=1}^{G} x_{j,k}^{\text{biofuel}}, \; j \in \tilde{P} \tag{8}$$

The biomass that is received at the plant, i.e. harvested biomass, multiplied by the plant efficiency, is then the output of biofuel that is delivered to the gas stations.

The corresponding equations for commodity c, e.g. heat, are

$$x_j^c \leqslant \bar{x}_j^c u_j, \quad j \in \tilde{P} \tag{9}$$

where $\bar{x}_j^c$ is the capacity, and

$$a_j^c \sum_{i=1}^{S} b_{i,j} = x_j^c, \; j \in \tilde{P} \tag{10}$$

where a_j^c is the efficiency. The produced biofuel in plant j is transported to gas station k for the cost $t_{j,k}$. The value of producing commodity c is given by the price p_j^c.

The cost for setting up a gas station k with the capacity $\bar{x}_k^{\text{biofuel}}$ is e_k. The cost for handling biofuel at the station is c_k. Similar to the plant model, the gas station is also modeled using capacity and mass flow equations; i.e.

$$\sum_{l=1}^{D} x_{k,l}^{\text{biofuel}} \leqslant \bar{x}_k^{\text{biofuel}} u_k, \quad k \in \tilde{G} \tag{11}$$

and

$$\sum_{j=1}^{P} x_{j,k}^{\text{biofuel}} = \sum_{l=1}^{D} x_{k,l}^{\text{biofuel}}, \quad k \in \tilde{G} \tag{12}$$

must hold.

The demand for car fuel in region l is modeled by

$$\sum_{k=1}^{G} x_{k,l}^{\text{biofuel}} + x_l^{\text{fossil}} = d_l, \quad l \in \tilde{D} \tag{13}$$

where d_l is the demand. The corresponding transportation cost is $t_{k,l}$, which is interpreted as the driving cost for people driving from region l to gas station k. The fossil fuel is assumed to be available for a price p_l^{fossil}.

Given the costs and prices, the objective function is defined as

$$\begin{aligned} f(b,x,u) = {} & \sum_{i=1}^{S}\sum_{j=1}^{P}(c_i + t_{i,j})b_{i,j} + \sum_{j=1}^{P} e_j u_j \\ & + \sum_{j=1}^{P}\sum_{k=1}^{G}(c_j + t_{j,k})x_{j,k}^{\text{biofuel}} \\ & + \sum_{j=1}^{P} c_j x_j^c - \sum_{j=1}^{P} p_j^c x_j^c + \sum_{k=1}^{G} e_k u_k \\ & + \sum_{k=1}^{G}\sum_{l=1}^{D}(c_k + t_{k,l})x_{k,l}^{\text{biofuel}} \\ & + \sum_{l=1}^{D} p_l^{\text{fossil}} x_l^{\text{fossil}} \end{aligned} \tag{14}$$

The different summands in the objective function are:

(1) Cost of biomass production (parameter) plus the transportation cost (parameter) times the amount of biomass that is actually taken (variable).
(2) Plant setup cost (parameter) times the 'decision' (variable) of building a plant.
(3) Plant production cost (parameter) plus transportation cost of biofuel from the plant to the gas stations (parameter) times the amount of methanol being produced at the plant (variable).
(4) Plant production cost (parameter) times the amount of heat produced (variable).
(5) Minus the price of heat (parameter) times the amount of heat produced (variable).
(6) Plus the setup cost of gas stations (parameter) times the 'decision' (variable) of setting up a gas station.
(7) Gas station handling cost (parameter) plus transport cost from the gas station to the living area (parameter) times the amount of biofuel taken from the gas station (variable).
(8) Price of fossil fuel (parameter) times the amount of fossil fuel taken (variable).

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Table IV. Parameters for the plants [12].

Parameters	Units	Value
Conversion methanol	%	60
Conversion heat	%	10
Load hours	h	7200
Interest rate	%	10
Economical lifetime	Years	25

Finally, define the FLP as a linear mixed integer program:

$$\begin{aligned}&\min_{b,x,u}[f(b,x,u)]\\&\text{s.t.}\\&(6)-(14)\\&\quad b_{i,j}, x_{j,k}^{\text{biofuel}}, x_j^c, x_{k,l}^{\text{biofuel}}, x_l^{\text{fossil}} \geqslant 0,\\&\quad i\in\tilde{S}, j\in\tilde{P}, c\in\tilde{C}, k\in\tilde{G}, l\in\tilde{D}\\&u_j\in\{0,1\}, u_k\in\{0,1\},\ \ j\in\tilde{P}, k\in\tilde{G}.\end{aligned} \tag{15}$$

2.3. Input data and scenarios

Different positions of plants in Austria are used in the model. The possible plants studied are geographically distributed every 0.33° in longitude and latitude all over the country. The optimal geographical position will be selected for three scenarios. For each scenario, one considers alternatively the production of one kind of biofuel blend, M5, M10 and M20. The plants are defined by the parameters described in Table IV.

The price for heat is assumed to be 0.054 € kWh^{-1} [13]. Once the plants are selected for each scenario, the competition with fossil fuel is conducted, and the influence of the production of heat and the raw material prices are analyzed. Finally, the consequence of the use of methanol blend on the carbon emissions is emphasized.

3. RESULTS AND DISCUSSION

3.1. Blend

In Austria, fossil fuel should be replaced by 10 and 20% biofuels by the years 2010 and 2020, respectively. To achieve these targets, different methanol–gasoline blends were studied: M5, M10 and M20. For each of these scenarios, the model finds the number of plants needed to fulfill the demand, their size and their location. The optimal locations of the methanol plants for the three scenarios of blends are presented in Table V together with their characteristics and different transport and production costs.

Austria had about 1 380 480 ha of arable lands in 2005. Producing M5, M10 or M20 would require 2.07, 4.08 or 8.19% of the arable lands respectively. Under these conditions, Austria would be self-sufficient in the production of methanol blend using poplar biomass. For the production of M10, two methanol plants were the optimal situation ahead of one bigger methanol plant. The same can be noticed for the production of M20, where three methanol plants were selected (Figure 4).

Concerning the transport costs, one can notice that for biomass they increase slightly as the capacities of the plants increase, since more raw materials are needed. At the same time the transport costs of the fuel decrease (from 2.04 to 1.31 € GJ^{-1}). The distances for delivering the biofuel remain high (over 460 km for each scenario), since the far west of the country has to be delivered. For every scenario, setting up a methanol plant closer to the biomass supply has been a better choice than building it closer to the fuel demand.

Meanwhile, the total cost of methanol decreases as the capacity of the plant increases. The cheaper methanol is found for two plants from the M20 scenario. For this scenario, one can notice that the third plant produces the most expensive fuel of the three scenarios; this plant also has the lowest capacity.

3.2. Geography and cost

The methanol cost depending on the geographical position of the plant for the M5 scenario is shown in Figure 5. These costs are calculated by assuming a virtual plant at each grid point alternatively. The calculations were also carried out for each result of the other scenarios presented in Table V, which gave similar maps.

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Table V. Results of the optimal location of the methanol plant in Austria for different methanol blends.

	Units	M5	M10	M10	M20	M20	M20
Longitude		13.99	13.99	15.97	13.99	16.63	15.97
Latitude		48	48	48.33	48	48.33	48.33
Capacity	$t_{biomass}\,day^{-1}$	846	928	765	1429	1231	725
Methanol production	$m^3\,year^{-1}$	143 891	287 781			575 562	
Area of arable land	ha	26 400	54 300			110 600	
Arable land share	%	2.1	4.1			8.2	
Biomass transports							
Mean	€ GJ^{-1}	1.60	1.62	1.56	1.73	1.61	1.55
Max	€ GJ^{-1}	1.80	1.83	1.71	2.05	1.78	1.70
Max distance	Km	25.3	26.9	21.3	37.3	24.5	20.6
Production costs	€ GJ^{-1}	16.58	15.13	18.33	12.41	14.42	19.36
Fuel transports							
Mean	€ GJ^{-1}	0.91	0.88	0.58	0.95	0.75	0.68
Max	€ GJ^{-1}	2.04	2.04	1.31	2.04	1.76	1.52
Max distance	Km	461	461	285	461	394	336
Fuel cost							
Min	€ GJ^{-1}	22.33	20.91	24.04	18.30	20.19	25.07
Max	€ GJ^{-1}	24.18	22.72	25.16	20.15	21.75	26.40
Mean	€ GJ^{-1}	23.05	21.54	24.44	19.06	20.74	25.56
Max	€ l^{-1}	0.38	0.36	0.40	0.32	0.33	0.42
Extra products (heat)	GWh $year^{-1}$	126	138	114	213	183	108

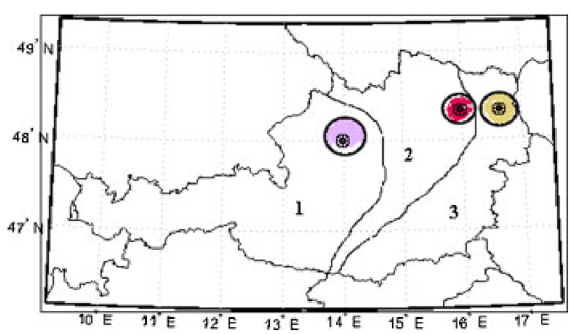

Figure 4. Geographical results for the production of M20 in Austria: the dots inside the circles represent the arable land that could possibly deliver the raw material to the plants (represented by the stars). The areas 1–3 represent the three zones where each plant would deliver methanol.

Figure 5 presents the areas for different costs of methanol regarding the location of the plant, for the M5 blend. The lowest production cost would then be obtained with the plant located in the north of the country, where the total methanol cost is around 0.38 € l^{-1}. This area corresponds to the area selected by the model (Table V). The

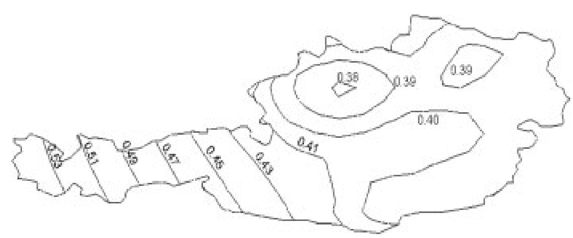

Figure 5. Cost of methanol (in € l^{-1}) regarding the position of a 846 $t_{biomass}\,day^{-1}$ plant. A methanol–gasoline blend M5 is considered.

figure shows that a change in the position of the plant could vary the cost by 2.5% (from the 0.38 to the 0.39 € l^{-1} area). Thus, changes in positions within a cost area will influence the methanol cost less than 2.5%.

3.3. *Biofuel versus gasoline*

Gasoline has an energy density of 32 MJ l^{-1}. Pure methanol has an energy density of 15.7 MJ l^{-1}. A higher amount of methanol is then needed to drive the same distance as with gasoline. Hence, the

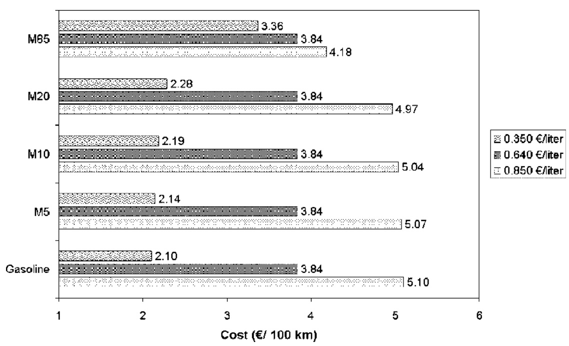

Figure 6. Costs of different methanol blends in €/100 km, for three gasoline prices (0.35, 0.64 and 0.85 € l^{-1}) and a methanol cost of 0.3 € l^{-1}.

methanol and gasoline costs are important for the choice of fuel by the costumer.

Figure 6 presents the cost in €/100 km for gasoline and methanol blends (M5, M10, M20 and M85). The gasoline consumption of a personal car is here assumed to be 5 l/100 km. This figure compares the cost of pure conventional gasoline with biofuel, i.e. methanol blends.

The break even point is for a cost of gasoline of 0.640 € l^{-1}, where all the fuels have the same cost (3.84 €/100 km). The break even line between gasoline and the different methanol blends is reached when the ratio of the methanol cost over the gasoline cost equals the ratio of the methanol energy density over the gasoline energy density. In other words, as soon as the cost of gasoline is over 0.640 € l^{-1} (assuming the methanol cost is 0.3 € l^{-1}), driving with a higher blend of methanol would be more attractive than driving with gasoline.

3.4. Methanol production with heat recovery

From the production of methanol, one can consider the production of heat as a by-product. Producing heat has the advantage for the methanol plant to have extra income. Heat can be sold to a heating network or to some nearby factories. The influence of heat sale on the methanol cost is presented in Table VI.

Considering the heat production in the methanol plant with an efficiency of 10%, the fuel cost would decrease about 12%. How fuel costs are influenced with respect to heat prices for different methanol blends is shown in Figure 7.

Table VI. Consideration of heat in the methanol cost for different blends.

	Units	M5	M10	M20
Initial cost	€ l^{-1}	0.393	0.375	0.352
Heat	GWh $year^{-1}$	126	138	168
Adapted cost	€ l^{-1}	0.345	0.327	0.304

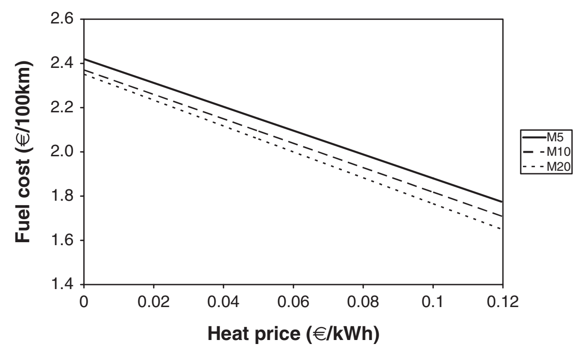

Figure 7. Impact of heat prices on the cost of methanol for three methanol blends.

As the heat price increases, the plant would earn extra incomes, and thus the fuel costs decrease. For instance, an increase of the heat price by 30% would reduce the costs of M5 by 16%, M10 by 18% and M20 by 20%. In order to sell the most competitive methanol as possible, production with heat recovery would help the plant reducing its costs. Selling excess heat would be one mean to reach this goal. The location of the methanol plant should then be decided regarding the heat demand in the area either from private consumers or from industrial needs.

3.5. Biomass cost influence

The cost of biomass is the parameter that has the greatest influence on the final products. A sensitivity analysis on biomass production costs reveals the impact and the economic viability of a plant. In this analysis, biomass costs vary between 30 and 120 € m^{-3} (Figure 8).

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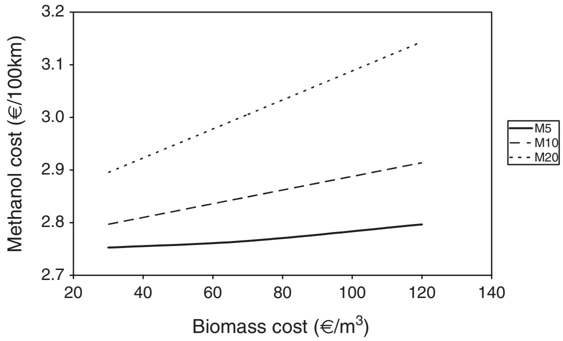

Figure 8. Influence of biomass production costs on the methanol cost for three methanol blends.

One should notice that an increase of 50% in biomass production costs will raise the cost of M5, M10 and M20 by 0.5, 2 and 4%, respectively. The production of M20 would be the most sensible as it requires more biomass. For these three blends, the costs of biomass production and biomass transport represent 24, 37 and 49% of the total methanol cost.

3.6. Carbon emissions

Different CO_2 emissions (as well as elemental carbon) per fuel are presented in Table VII. From this table, one can notice that the emissions of carbon or CO_2 would decrease by 2.5, 5.2 and 11% if one uses M5, M10 or M20, respectively. To achieve the goal set by the European Parliament, a blend of gasoline with 33% methanol would be necessary to decrease the carbon emissions (from cars only) by 25%. It was totalized in 2005, 5.6 million cars in Austria [14]. Figure 9 shows how emissions reduction and carbon price are depending on each other regarding the methanol blends.

In the figure one assumes that all the cars run with a methanol blend. Considering M20, this would decrease the CO_2 emissions by 1.7 Mt year^{-1}, which is equivalent to 2% of the total Austrian carbon emissions in 2003 [15]. The total saving on the use of M20 would amount to 9 M€ year^{-1} in carbon cost. The carbon emissions and emission cost would be lower for higher methanol blends; i.e. if one considers M85, the emissions would be decreased to 4 Mt year^{-1} of CO_2 and the cost reduction becomes 60 M€ year^{-1}.

Table VII. Emissions from different fuels and difference between gasoline and the methanol blends expressed in carbon prices (a carbon price of 20 € t^{-1} is assumed).

Fuel	CO_2 emissions (kg/100 km)	Carbon emissions (kg/100 km)	Carbon cost (€/100 km)
Gasoline	18.57	5.07	—
M5	18.10	4.94	−0.003
M10	17.61	4.80	−0.005
M20	16.54	4.51	−0.011

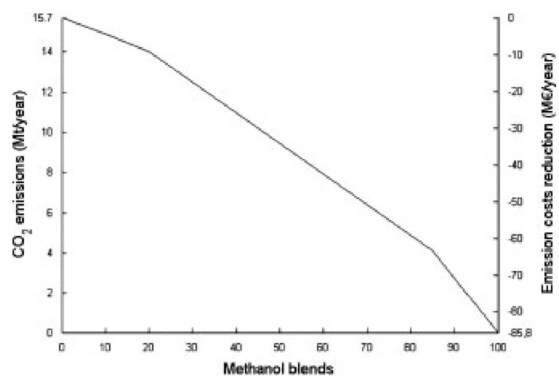

Figure 9. CO_2 emissions and emission price reduction in regard to the methanol blends.

4. CONCLUSIONS

This article presents a mixed integer linear programming model that determines the optimal sizes and locations of biomass-based methanol plants with heat recovery. The supply in raw material is characterized by the location and the yield of poplar coppice, and the demand in car fuel is characterized by the location of the gas stations in the studied country. Owing to new EU goals, biofuel will probably be introduced in large-scale all over Europe. It is thus important to optimize the investment and operation costs, which include the whole energy chain from biomass supply to delivery of methanol at the gas stations. The model presented in the current paper was found to be a useful tool in this planning process.

Three scenarios for optimal locations of methanol plants in Austria have been studied. For each scenario, different blends of methanol were analyzed. Producing methanol blends M5,

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M10 or M20 from poplar biomass would require about 2, 4 or 8% of total arable lands in Austria, respectively. Consequently, Austria has the potential in supplying domestic biomass to attain the national biofuel targets of 10 and 20% in 2010 and 2020.

By-production of heat decreases the biofuel cost by 12%. This would have a great impact concerning the cost of blends to become more competitive with fossil fuel. An increase of the heat price by 30% would decrease the cost of M20 by 20%. The Austrian carbon emissions are considered. With the use of the biofuel M20, the Austrian total emissions could decrease by 2%, and would lower the cost on fossil fuel emissions by 9 M€ year^{-1}.

An extension of the model would be to study the production of power and analyze the price and the demand of each product.

NOMENCLATURE

a_j^{biofuel} = efficiency for producing biofuel at the plant j
a_j^c = efficiency for producing commodity c at the plant j
AC = annual cost (€ year^{-1})
$\bar{b}_i$ = available biomass at the supply region i (t)
$b_{i,j}$ = amount of biomass delivered from supply region i to plant j (t)
c_i = cost for producing biomass in the supply region i (€ t^{-1})
c_j = cost for producing biofuel at the plant j (€ GJ^{-1})
c_k = cost for handling biofuel at the gas station k (€ GJ^{-1})
C = number of additional commodities
$\tilde{C}$ = set of additional commodities
C_{Tractor} = transportation cost by tractor (€ GJ^{-1})
C_{Truck} = transportation cost by truck (€ GJ^{-1})
Cost_a = cost of equipment for the plant a (€)
Cost_b = cost of equipment for the plant b (€)
d = actual distance (km)
d_l = demand of car fuel in the region l (GJ)
D = number of demand regions
$\tilde{D}$ = set of demand regions
e_j = cost for setting up plant j (€)
e_k = cost for setting up gas station k (€)
G = number of gas stations
$\tilde{G}$ = set of gas stations
IR = interest rate
p_j^c = price of the commodity c produced at the plant j (€ GJ^{-1})
p_l^{fossil} = price of fossil fuel in the region l (€ GJ^{-1})
P = number of plants
$\tilde{P}$ = set of plants
R = scaling factor
S = number of biomass supply regions
$\tilde{S}$ = set of biomass supply regions
Size_a = size of the biofuel plant a (MW_{biomass})
Size_b = size of the biofuel plant b (MW_{biomass})
t_e = economical lifetime (years)
$t_{i,j}$ = cost for transporting biomass from supply region i to plant j (€ t^{-1})
$t_{j,k}$ = cost for transporting biofuel from plant j to gas station k (€ GJ^{-1})
$t_{k,l}$ = transportation cost from gas station k to region l (€ GJ^{-1})
TCR = total capital requirement (€)
u_j = binary variables, indicate if the plant j is in operation
u_k = binary variables, indicate if the gas station k is in operation
$\bar{x}_j^{\text{biofuel}}$ = capacity of the plant j (GJ)
$\bar{x}_k^{\text{biofuel}}$ = capacity of the gas station k (GJ)
$\bar{x}_j^c$ = capacity of commodity c at the plant j (GJ)
x_j^c = amount of commodity c that is produced at plant j (GJ)
$x_{j,k}^{\text{biofuel}}$ = amount of biofuel delivered from plant j to gas station k (GJ)
$x_{k,l}^{\text{biofuel}}$ = amount of biofuel sold at gas station k to costumers from demand region l (GJ)

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x_l^{fossil} = amount of fossil fuel sold to costumers from demand region l (GJ)

Subscripts

i = biomass supply number
j = plant number
k = gas station number
l = demand region number

Superscript

c = commodity number

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REFERENCES

1. EUROSTAT. Data of various years available online at http://epp.eurostat.ec.europa.eu (accessed on 26 February 2007).
2. COM 2006. *Renewable Energy Road Map—Renewable Energies in the 21st Century*: *Building a More Sustainable Future*. Communication from the Commission to the Council and the European Parliament, 2007. COM(2006) 848 final.
3. Wolsey LA. *Integer Programming*. Wiley: New York, 1998.
4. Schmid E, Balkovic J, Moltchanova E, Skalsky R, Poltarska K, Müller B, Bujnovsky R. Bio-physical process modeling for EU25—concept, data, methods and results. *Final Research Report for the EU-FP6 Research Project INSEA*, International Institute of Applied System Analysis (IIASA), Laxenburg, Austria, 2006.
5. Williams JR. The EPIC model. In *Computer Models of Watershed Hydrology*, Singh VP (ed.). Water Resources Publication: Highland Ranch, CO, U.S.A., 1995; 909–1000.
6. Börjesson P, Gustavson L. Regional production and utilization of biomass in Sweden. *Energy* 1996; **21**(9):747–764.
7. Hamelinck CN, Faaij APC. Future prospects for production of methanol and hydrogen from biomass. *Journal of Power Sources* 2002; **111**:1–22.
8. Katofsky RE. *The Production of Fluid Fuels from Biomass*. Center for Energy and Environmental Studies/Princeton University: Princeton, 1993.
9. Craig KR, Mann MK. Cost and performance analysis of biomass-based integrated gasification combined-cycle (BIGCC) power systems. *Report from National Renewable Energy Laboratory*, Golden, CO, 1996. NREL/TP-430-21657.
10. Parsons EL, Shelton WW, Lyons JL. Advanced fossil power systems comparison study. *Final Report*, prepared for National Energy Technology Laboratory, Morgantown, U.S.A., 2002.
11. AMF-EA Engineering. *Methanol Refueling Station Costs*. Prepared for American Methanol Foundation by EA Engineering, Science and Technology, Inc., Silver Spring, U.S.A., 1999.
12. Hansson J. Combined heat/power plants versus the co-generation of heat and alternative transportation fuels—an energy-economy model based evaluation of cost-efficiency for the EU. *Thesis for Master of Science in Environmental Science with an Emphasis on Problem Solving*, Chalmers University of Technology, Sweden, 2003.
13. Ecoheatcool and Euroheat & Power. Ecoheatcool work package 1. The European heat market. *Final Report*, 2006.
14. Statistik Austria. http://www.statistik.at (accessed on 03 March 2007).
15. UNEP/GRID—Arendal, United Nations Environment Programme. http://www.grida.no (accessed on 05 March 2007).

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Optimizing biodiesel production in India

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Abstract

India is expected to at least double its fuel consumption in the transportation sector by 2030. To contribute to the fuel supply, renewable energies such as jatropha appear to be an attractive resource for biodiesel production in India as it can be grown on waste land and does not need intensive water supply. In order to produce biodiesel at a competitive cost, the biodiesel supply chain - from biomass harvesting to biodiesel delivery to the consumers - is analyzed. A mixed integer linear programming model is used in order to determine the optimal number and geographic locations of biodiesel plants. The optimization is based on minimization of the costs of the supply chain with respect to the biomass, production and transportation costs. Three biodiesel blends are considered, B2, B5 and B10. For each blend, 13 scenarios are considered where yield, biomass cost, cake price, glycerol price, transport cost and investment costs are studied. A sensitivity analysis is carried out on both those parameters and the resulting locations of the plants. The emissions of the supply chain are also considered. The results state that the biomass cost has most influence on the biodiesel cost (an increase of feedstock cost increases the biodiesel cost by about 40%) and to a lower effect, the investment cost and the glycerol price. Moreover, choosing the right set of production plant locations highly depends on the scenarios that have the highest probability to occur, for which the production plant locations still produce a competitive biodiesel cost and emissions from the transportation are minimum. In this study, one set of plant locations happened to meet these two requirements.

Keywords: biodiesel, jatropha, plant location, India, supply chain.

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1. Introduction

In 2005, India consumed 30 million tons of oil in the transport sector, of which 29% is gasoline and 71% is diesel [1]. The Indian energy demand is expected to grow at an annual rate of 4.8% over the next couple of decades [2]. Many scenarios projected that India will at least double its oil consumption by 2030 [3], which will make India the third largest oil consumer in the world [4]. Biofuel production could potentially play a major role in the country.

A number of developmental activities are being taken up in the country for the production of biofuels, which include a 5% compulsory blend of ethanol in gasoline [2]. These trials are on in various state and the Government of India aims to increase the blends of biofuels with gasoline and diesel to 20% by 2017 [5].

Biodiesel has the advantage to be mixed with mineral diesel to any quantity, and its use does not require major changes on the engines as its properties are similar to those of diesel. The use of pure biodiesel in the transport sector lowers the emissions of soot by 60%, carbon monoxide and hydrocarbons by 50% and carbon dioxide by 80%. Nevertheless emissions of NO_x may vary by ±10% regarding the engine's combustion characteristics [6]. Sulfur dioxide is not emitted as no sulfur is contained in biodiesel due to its vegetable origin [7].

Considering biodiesel production, jatropha has attracted an increased interest since it is a drought-resistant perennial and grows well in marginal/poor soil. It is easy to establish, grows relatively well and produces seeds for 50 years. Its seeds have an oil content of 37% which can be combusted as fuel without refining [8]. Production of biodiesel in India plays a major role as it offers chances for social and rural development amongst poorest people, namely farmers in developing countries. By cultivating energy crops, these communities can diversify their crop portfolio, generate substantial incomes and hence facilitate economic and social development [9]. Producing renewable energy locally can thus offer a viable alternative but only if the projects are intelligently designed and carefully planned with local input and cooperation [10].

This study is focused on the supply chain of the biodiesel production based on jatropha, and the aim is to determine the optimal location of biodiesel plants for three blends, 2% (B2), 5% (B5) and 10% (B10). An analysis of the different parameters influencing the final biodiesel cost is considered as well as the sensibility of different combinations of plant locations in regards to the scenarios studied. In the following study, costs and prices are given in Rs, at the date of this study 1 Rs represents US$ 0.02 [11]. The base year for the currency is 2009.

2. Methodology

2.1. Feedstock

Jatropha seeds are harvested manually every year. The selected land may be owned by government, forest department, individual farmers or private industries. Over 40 million ha [12] of land from 28 states are estimated to be potential wasteland for growing jatropha. These lands include gullied and ravened land, upland with or without scrub, shifting cultivation area, degraded forest/pastures/grazing land and degraded land under plantation crop [13].

In order to realistically model biodiesel production in India, the biomass needs to be spatially located. Two spatial datasets were utilized in this approach, namely the 1 km^2 Global Land Cover (GLC-2000) [14] for South Asia and the Global Administrative Unit Layers (GAUL) [15]. Initially, total wasteland area was assigned to each state based on values taken from the literature

[16] (see Table 1). The South Asia regional land cover dataset taken from the GLC-2000 was used to spatially identify land cover within India. From a total of 47 land cover classes, 11 classes were identified as wasteland [12]. All data were then imported into a Geographic Information System (GIS) which attempted to assign per state, the total amount of identified wasteland area in the statistics to the spatial dataset. Finally, the spatially identified wasteland at 1km^2 resolution was aggregated to a 0.5 degree grid for further calculations (Figure 1). This aggregation is necessary in order to reduce computing time. Such a grid size provides 1,131 grid points across India providing an acceptable resolution at the country level.

Table 1
Total area of biomass potential in India by state

State	Biomass potential (Mha)
Andhra Pradesh	4.40
Arunachal Pradesh	1.00
Assam	1.46
Bihar	1.86
Goa	0.04
Gujarat	2.87
Haryana	0.26
Himachal Pradesh	0.00
Jammu & Kashmir	0.00
Karnataka	1.79
Kerala	0.10
Madhya Pradesh	6.62
Maharashtra	4.86
Manipur	1.26
Meghalaya	0.94
Mizoram	0.41
Nagaland	0.84
Orissa	1.89
Punjab	0.11
Rajasthan	5.69
Sikkim	0.21
Tamil Nadu	1.80
Tripura	0.13
Uttar Pradesh/ Uttranchal	1.21
West Bengal	0.26
Union Territories	0.06
Grand Total	40.04

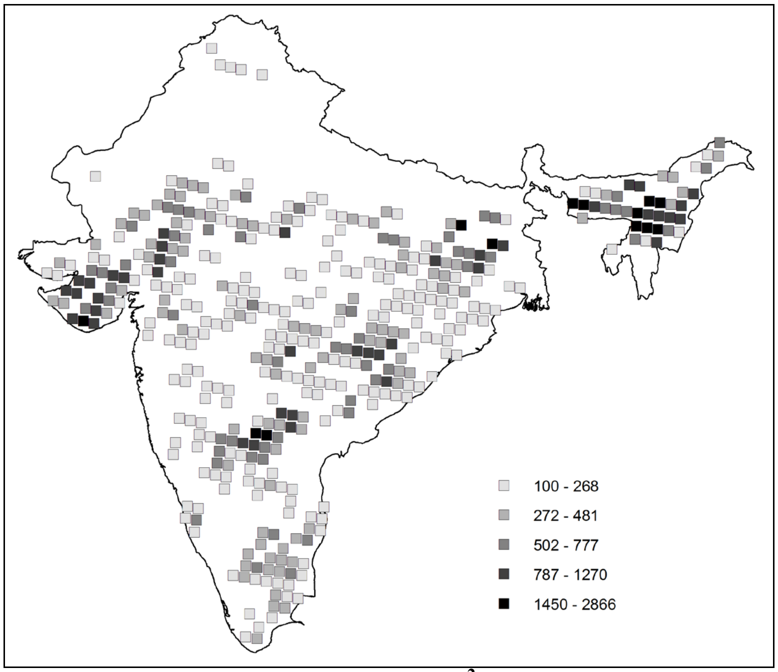

Figure 1. Indian identified areas (km^2) as wasteland for potential jatropha plantations. Areas under contention not included in map.

2.2. Transportation

In this study, two modes of transportation are selected: roadways/truck and railways/train. For each point on the grid, the distances driven by either truck or train to any other point were determined by GIS. A spatial network was created in the GIS using data on roads and railways from the Digital Chart of the World [17]. Truck transportation is applied when the biodiesel plant is located in a place without any railway facilities. The minimum distance that can be travelled by freight train is 100 km. Regarding the transportation cost, either one or the other transportation method is chosen.

The transportation costs are presented in Table 2. The cost for jatropha transportation by truck is derived from [18, 19]. In case of longer distances, the seed material can be transported by train after being harvested. The cost of jatropha transportation by train is derived from [20]. The biodiesel produced in the plant can also be transported by truck or train to the fuel stations for further blending and distribution. The choice of transportation depends on the availability of infrastructure, quantity and distance travelled between the plant and fuel station. The transportation cost of biodiesel by truck is derived from [18]. The transportation cost of biodiesel by train is derived from [20]. Loading and unloading costs are considered in the transportation costs; they represent the fix cost in the equations. Those costs are derived from [19, 21].

Table 2: Transportation cost for jatropha and biodiesel regarding the distance *d* driven.

	Unit	Truck	Train
Jatropha	Rs/t	$2d + 120$	$0.688d + 150$
Biodiesel	Rs/GJ	$0.055d + 1.22$	$0.032d + 4.65$

The emissions of CO_2 are considered to be 31.66 g_{CO2}/km/t by truck, and 4.48 g_{CO2}/km/t by train [22].

2.3. Biodiesel plant

The production of biodiesel from jatropha involves two steps: oil extraction and transesterification (explained below).

2.3.1. Oil extraction

In the oil extraction unit, crude oil is extracted from either using mechanical expeller or chemical extraction [23]. In this study, mechanical expeller is employed to expel oil from jatropha seed. According to Henning [24], an engine driven screw press yields 75-80% of oil, whereas the manually operated ram press achieved only 60-65%. The seeds are passed several times (normally 3 times) to the expeller in order to extract available oil from the seeds. Moreover, pretreatment of the seeds, like cooking can increase the oil yield of screw pressing up to 89% after single pass and 91% after dual pass [25]. A dual pass is considered in this study.

2.3.2. Transesterification

In this process the crude oil reacts with alcohol to form esters and glycerol in the presence of a catalyst. The manufacturing process of biodiesel can be carried out in two ways, either batch or continuous flow process [26]. The continuous flow process method is selected for large plants, which are less expensive and shorter processing time utilizes the resources in a continuous manner operating at 60°C. It comprises of a catalyst reactor, a biodiesel reactor, settling and washing tanks. During the transesterification process, the filtered crude oil (anhydrous) is allowed to react with methanol in the presence of an alkali catalyst like NaOH to produce methyl ester (biodiesel).

According to Chitra et al. [27], maximum ester yield of 98% is possible using 20% methanol and 1% of NaOH at 60°C reaction temperature after 90 minutes of minimum reaction time. The main product of transesterification is biodiesel which could be blended with diesel and used as fuel for the transportation. The by-products produced are glycerol, which can be refined and used in cosmetic industries, and oil cake that can be used as a fertilizer [23].

The study is based on a biodiesel plant size of 150,000 $t_{biodiesel}$/year which is considered has a large production plant [28]. Economy of scale is not considered in this study and should be taken into account in further research. The characteristics of the plant can be found in Table 3.

Table 3
Parameters for a biodiesel production plant of 150,000 $t_{biodiesel}$/year [26, 28]

Parameter	Unit	Value
Biodiesel production	$kg_{biodiesel}/t_{seeds}$	300
Glycerol production	$kg_{glycerol}/t_{seeds}$	29
Oil cake production	kg_{cake}/t_{seeds}	680
Annual cost	MRs/year	56.4
Production cost	Rs/GJ	237

3. Optimization and scenarios

The aim of this study is to determine the optimal locations of biodiesel plants in India under different scenarios. A mixed integer linear programming model [29] is used to optimize the supply and delivery of biodiesel. A detailed description of the model is given in Leduc et al. [30, 31]. The model is extended to the production of biodiesel where the by-products considered are glycerol and oil cake. In Figure 2, the model is schematically depicted as a graph with nodes and arcs. A continuous variable is associated to each arc, representing delivery of biomass, biodiesel or fossil fuel. Binary variables are associated to the plant nodes, modeling when the current plant is in operation.

The supply of biomass is restricted in each supply region by the available amount that can be harvested. Plants are modeled using energy balance equations, combined with capacity constraints for production or delivery. Depending on whether a plant is built to produce biodiesel, constraints modeling these specific relations are included. A vehicle fuel demand constraint, which considers competition between biodiesel and fossil fuels, is defined for each demand region.

The objective is to minimize the overall costs in order to fulfill the demands for vehicle fuel. The cost function that is minimized includes the cost for supply of biomass, operation of production plants, investment in plants, and transportation of biomass and biodiesel.

Evaluating the model by solving the optimization problem generates the optimal locations, sizes and configurations of production plants. The solution also includes the optimal amount of the domestically biomass that shall be supplied, and from which region it shall be taken.

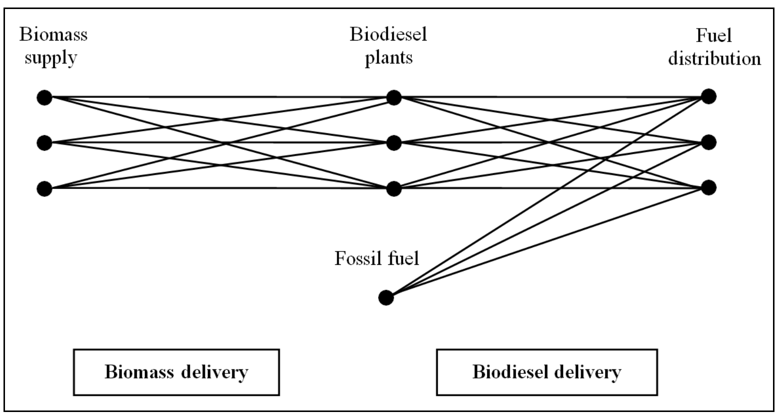

Figure 2: Scheme of the model.

The parameters and scenarios are presented in Table 4. Different blends are studied: B2, B5, and B10. For each blend there is one base scenario (run 1) and 12 more runs where the yield, biomass cost, cake price, glycerol price, transport cost and investment costs vary by ±50% alternatively. In total, 39 runs are then considered. The calculations are based on a transport fuel consumption of 620 TWh/year (of which 71% is diesel) for the year 2020 [1, 4]. Each parameter and the resulting production plant locations are analyzed.

A further analysis is carried out to study the consequences of the choice of one set of production plants when another scenario occurs. For the scenarios S1-S13, the resulting locations of production plants are considered (P1-P13). For each of these sets of plants, the biodiesel cost is recalculated for the other scenarios. The difference in emissions from the transportation between the scenarios is also calculated.

Table 4
Scenarios studied for each blend

Scenario number	Yield (t/ha)	Truck transport cost change (%)	Biomass cost (Rs/kg)	Cake price (Rs/kg)	Glycerol price (Rs/kg)	Investment cost change (%)
1	3 [32]	0	6 [33]	1 [32]	60 [32]	0
2	**4.5**	0	6	1	60	0
3	**1.5**	0	6	1	60	0
4	3	**50**	6	1	60	0
5	3	**-50**	6	1	60	0
6	3	0	**9**	1	60	0
7	3	0	**3**	1	60	0
8	3	0	6	**1.5**	60	0
9	3	0	6	**0.5**	60	0
10	3	0	6	1	**90**	0
11	3	0	6	1	**30**	0
12	3	0	6	1	60	**50**
13	3	0	6	1	60	**-50**

4. Results and discussion

The results are similar for every blend. The scenarios 1, 2, 3, 4 and 5 give different results on the geography of the plants. Scenarios 6 to 13 give the same plant distribution as scenario 1 since the parameters changed are indeed not geographically dependent. The different locations for the different blends and scenarios are depicted in Figure 3. For the biodiesel production of B2, B5 and B10, an availability of land of respectively 1.2, 3.2, 6.4 Mha is needed.

Those production plants are mainly located in the center of the country, following the location of the biomass production. For instance for the blend B10, the northern limit of the locations of the production plants follow the same limit of the northern biomass production location. Distances for biomass transportations vary between 25 and a maximum of 100 km regarding the production plant, whereas the distances for biodiesel distribution can be as high as 1,200 km (for blend B2 for instance) as the model is built in order to meet the fuel demand across the country.

For the blend B2, three production plants out of seven keep the same location for all the scenarios. Twelve plants out of seventeen keep the same locations for the blend B5, and twenty six plants out of thirty one keep the same location for the blend B10. The differences in the locations of the production plants between the scenarios are then relatively small. The optimal location is further analyzed in the sections 4.2 and 4.3.

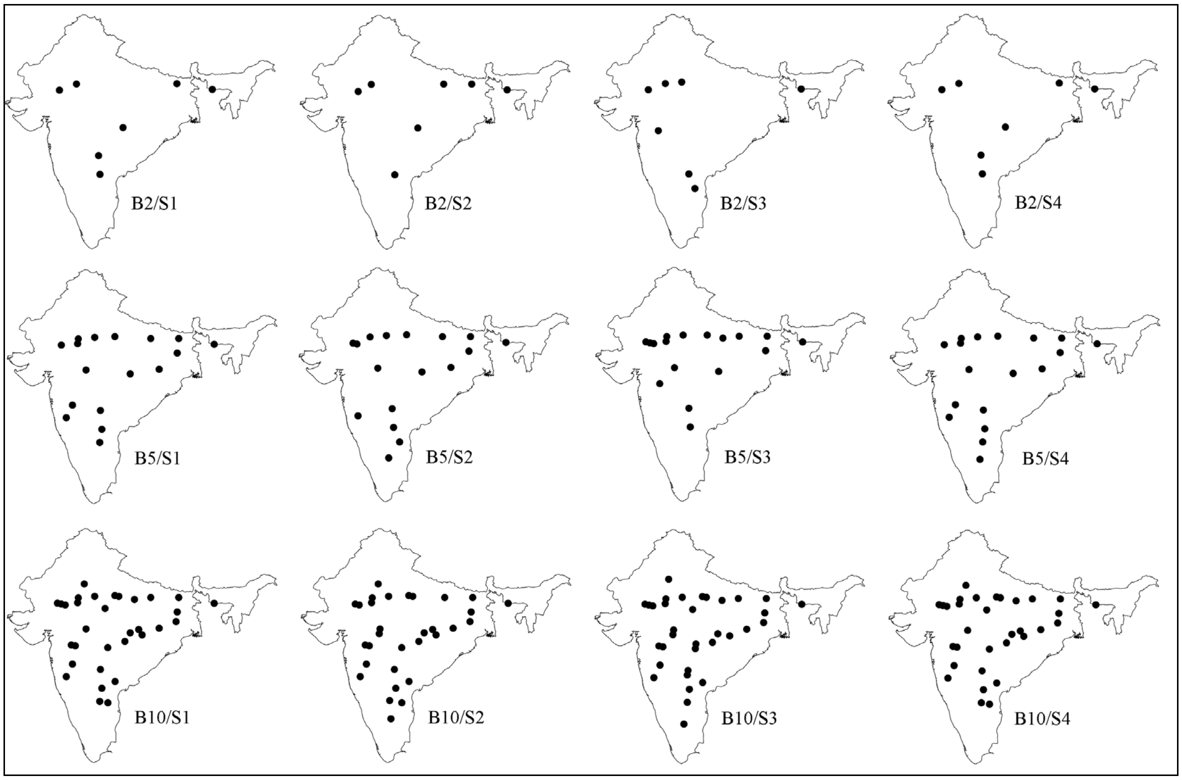

Figure 3. The first, second and third rows show the production plant locations for the B2, B5 and B10 scenario respectively. From left to right, scenarios S1, S2, S3 and S4 are presented (the S5 scenario is not presented as it is similar to S4). Areas under contention not included in map.

4.1. Sensitivity analysis

The influence of the parameters studied is presented in Figure 4. The variations in the biodiesel cost presented are the mean values of the change in biodiesel cost with regard to the base scenario (scenario 1).

The parameter that has the highest influence on the biodiesel cost is the biomass cost: a change of the biomass cost by 50% would indeed increase the biodiesel cost by 35%. An increase of 50% of the investment cost would increase the final biodiesel cost by 18%. The glycerol price and the transportation cost have both strong influences on the biodiesel cost: an increase of 50% of the transportation cost/glycerol price would increase/decrease the final biodiesel cost by 9%. The cake price has less influence (about 5% for a 50% change), and of less influence is the yield. As the cost of biomass is the most sensible parameter on the final biodiesel cost, decreasing the biomass yields would then increase the biomass costs and then increase the biodiesel cost consequently. In this study, the yield is not dependent of the biomass cost, and vice versa due to lack of data on this relationship. The biomass yield has therefore less influence on the cost than expected. A further analysis is carried out in section 4.2 regarding the effect of the plant locations.

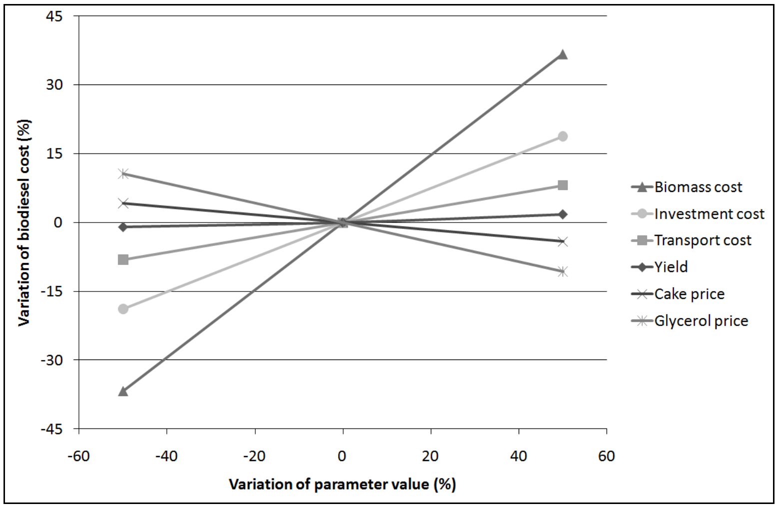

Figure 4. Parameter sensitivity. The reference cost of biodiesel in this analysis is 23.7 Rs/l.

4.2. Analysis of the plant locations

The resulting locations of the biodiesel plants from the different scenarios for blend B10 are considered. The four sets of plant locations presented in Figure 3 are considered. Those plant locations are denoted as P1, P2, P3 and P4. The plant locations are fixed, and one studies the consequences on the final biodiesel cost if another scenario would occur. Figure 5 shows such effect for each set of plant locations found. For instance, if one considers the optimal set of plant locations from the scenario 3 (P3), and if scenario 6 (S6) occurs; the biodiesel cost would be around 32 Rs/liter.

One notices that the biomass cost has a major influence (change in the costs by ±40%) for each location. For each set, the biodiesel cost was calculated regarding each scenario. Whatever the scenario that occurs, the biodiesel cost remains almost the same. The reason for the relatively small difference in cost (the bars for a scenario have almost the same height) is that the optimal sets of locations are almost the same in all scenarios; at most five production plant locations out of thirty one are relocated between scenarios. All set of plants are equivalent in term of cost and in this case, the optimal set cannot be determined only by the costs. Considering the emissions would then be another criterion.

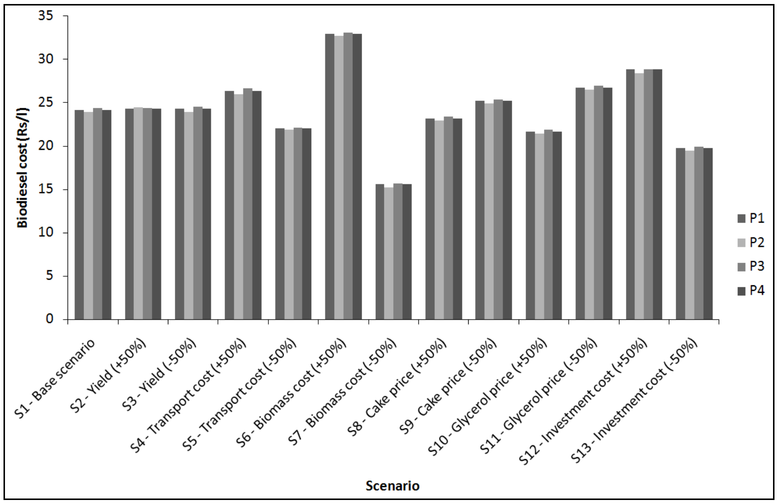

Figure 5. Influence of the scenarios on the biodiesel cost for four production plant locations.

4.3. Emissions

Here only the emissions from the transport are considered, since the plant studied remains the same for each scenario. Transportations are done by truck or train depending of the distance covered as presented in section 2.2. Figure 6 shows the CO_2 emissions with regard to the different scenarios for the sets of production plants described above. For instance, considering the set of plant locations P1, and the scenario S3, the CO_2 emissions would reach 23 Mt. The scenario that happens to be the most sensitive in terms of emissions is the scenario S3, when the yields drops by 50%; for all sets of locations, if it occurs, the emissions would increase by at least 15 Mt of CO_2. In other words, if the yield drops by 50%, emissions will thus increase due to higher transport distances to collect the raw material. Regarding the set of plant locations, the set P3 would be the most attractive: whatever the scenario that may occur, the emissions would be lower than the calculated ones from the scenario S3.

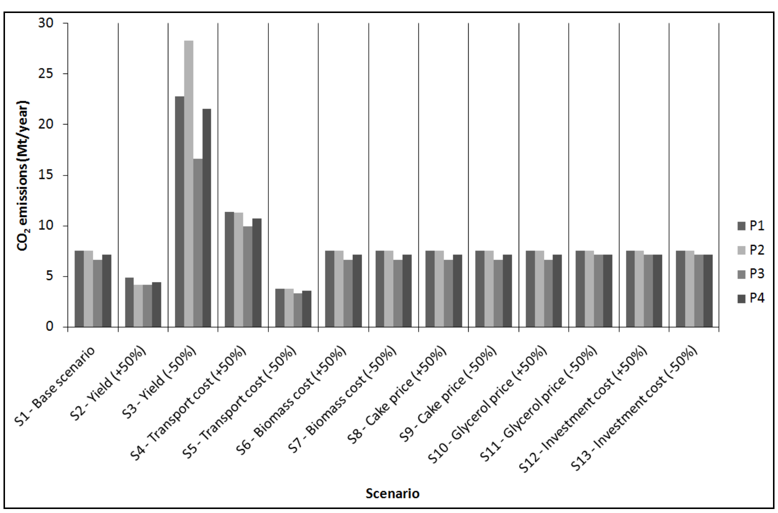

Figure 6. Influence of the scenarios on the CO_2 emissions from the transportation for four production plant locations.

A similar analysis can be done for the blends B2 and B5. In these cases, the plant locations the most attractive would be the location sets obtained from the scenario 3 and 4 for the blends B2 and B5 respectively. In the first case the plants are located in the vicinity of high biomass yields, and for a higher biodiesel production, the plants would be spread within the center of the country.

5. Conclusion

The supply chain of the biodiesel production has been studied for India, considering three different national targets on blends: B2, B5 and B10. For each blend, the geographical locations of the biodiesel production plants have been determined. The influence of important parameters such as yield, biomass cost, cake price, glycerol price, transport cost and investment costs have been analyzed and the influence of the selected locations on the costs and the emissions have been considered. The results show that the biomass cost has a major influence on the biodiesel production cost, and the investment cost, the transportation costs and the glycerol price have a relatively lower importance. Finally, choosing the most appropriate set of plant locations is a matter of analyzing both costs and emissions regarding different realistic scenarios. For each biodiesel blend, an optimal set of plant locations was determined: the biodiesel costs remained slightly the same, but the selection of the set could be determined from an emission point of view.

6. Acknowledgement

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7. References

[1] IEA. Oil in India in 2006. www.iea.org/Textbase/stats; 2009 [accessed 19-01-2009].

[2] J.B. Gonsalves, An assessment of the biofuels industry in India, United Nations conference on trade and development, 2006. Available at: www.unctad.org/en/docs/ditcted20066_en.pdf.

[3] Integrated energy policy: report of the expert committee - government of India planning commission, New Delhi, 2006, p. 182.

[4] IEA, World energy outlook 2006, Oil market outlook, International Energy Agency, 2006, p. 601.

[5] PIB. Focus on plantations, processing and production technologies. www.pib.nic.in; 2009 [accessed 20-01-2009].

[6] B.K. Barnwal, M.P. Sharma, Prospects of biodiesel production from vegetable oils in India, Renew and Sustain Energy Rev 9 (2005) 363-378.

[7] C.R. Coronado, J.A. de Carvalho Jr, J.L. Silveira, Biodiesel CO2 emissions: A comparison with the main fuels in the Brazilian market, Fuel Process Technol 90 (2009) 204-211.

[8] A. Mateos, Biodiesel: production process and main feedstocks, Energïa J 1 (2007).

[9] S. Lele. The cultivation of Jatropha curcas (Ratan Jyot). www.svlele.com; 2008 [accessed 12-12-2008].

[10] A.H. Demirbas, I. Demirbas, Importance of rural bioenergy for developing countries, Energy Conv and Manag 48 (2007) 2386-2398.

[11] Reserve Bank of India, India's Central Bank. www.rbi.org.in/home.aspx; 2009 [accessed 03-02-2009].

[12] L. Panichelli, E. Gnansounou, GIS-based approach for defining bioenergy facilities location: A case study in Northern Spain based on marginal delivery costs and resources competition between facilities, Biomass and Bioenergy 32 (2008) 289-300.

[13] L. Kumar, Biofuels: the key to India's sustainable energy needs, Risø international energy conference, Risø, 2005. Available at: www.risoe.dtu.dk/rispubl/SYS/syspdf/ris-r-1517.pdf.

[14] JRC. The global land cover map for the year 2000. www-tem.jrc.it/glc2000; 2008 [accessed 10-11-2008].

[15] FAO. GeoNetwork. www.fao.org/geonetwork; 2008 [accessed 12-11-2008].

[16] A. Adholeya, P.K. Dadhich, Production and technology of bio-diesel: seeding a change, TERI ed, 2008.

[17] Digital chart of the world server. www.maproom.psu.edu/dcw; 10-10-2008 [accessed 2008].

[18] Personal Communication: Uma Maheswari Agencies, Indian Oil Dealers, Nanjiampalayam Bye-pass Road. Dharapuram, India, 2009 [21-01-2009].

[19] Supplychainmanagement. www.supplychainmanagement.in; 2009 [accessed 15-04-2009].

[20] A. Kumar, S. Sokhansanj, P.C. Flynn, Development of a multicriteria assessment model for ranking biomass feedstock collection and transportation systems, Applied Biochemistry and Biotechnology 129 (2006) 71-87.

[21] Personal Communication: R. Hegde, Assistant Professor. Transportation cost of jatropha. College of Forestry, University of Agricultural Sciences, Bangalore Karnataka, India, 2009 [14-04-2009].

[22] R. Ramanathan, J.K. Parikh, Transport sector in India: An analysis in the context of sustainable development, Transp Policy 6 (1999) 35-45.

[23] W.M.J. Achten, L. Verchot, Y.J. Franken, E. Mathijs, V.P. Singh, R. Aerts, B. Muys, Jatropha bio-diesel production and use, Biomass and Bioenergy 32 (2008) 1063-1084.

[24] R.K. Henning, The jatropha booklet-a guide to the jatropha system and its dissemination in Zambia, 1st ed, Weissensberg, bagani GbR, 2000.

[25] P. Beerens, Screw-pressing of jatropha seeds for fueling purposes in less developed countries, Eindhoven, Eindhoven University of Technology, 2007.

[26] S. Lele. Plant design and drawings. www.svlele.com; 2008 [accessed 12-12-2008].

[27] P. Chitra, P. Venkatachalam, A. Sampathrajan, Optimisation of experimental conditions for biodiesel production from alkali-catalysed transesterification of jatropha curcus oil, Energy for Sustain Dev 9 (2005) 13-18.

[28] B. Amigun, F. Müller-Langer, H. von Blottnitz, Predicting the costs of biodiesel production in Africa: learning from Germany, Energy for Sustain Dev 12 (2008) 5-21.

[29] L. Wolsey, Integer programming, Wiley-Interscience New York, NY, USA, 1998.

[30] S. Leduc, D. Schwab, E. Dotzauer, E. Schmid, M. Obersteiner, Optimal location of wood gasification plants for methanol production with heat recovery, Int J Energy Res 32 (2008) 1080-1091.

[31] S. Leduc, J. Lundgren, O. Franklin, E. Dotzauer, Location of a biomass based methanol production plant: A dynamic problem in northern Sweden, Appl Energy In Press, Corrected Proof (2009).

[32] Report of the Committee on Development of Biofuel, New Delhi, Planning Commission Government of India, 2003.

[33] K.S. Dhillon, Jatrapha cultivation in Punjab, Biodiesel conference towards energy independence – focus on jatropha, New Delhi, 2006. Available at: http://biodiesel.nedfi.com/media/download_gallery/spland%20presentation.pdf.

OPTIMAL LOCATION OF ETHANOL LIGNO-CELLULOSIC BIOREFINERIES WITH POLYGENERATION IN SWEDEN

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Abstract

Ethanol produced from lignocellulosic biomass has great potential to contribute to reach the environmental goals of the transport sector set by the European Union (EU). Due to the growing demand of biomass based ethanol, the integration of ethanol production with combined heat and power plants is considered in this paper. An energy balance process model has been used to generate data for the production of ethanol, electricity, heat and biogas. The geographical position of such plants becomes of importance when using local biomass and delivering transportation fuel and heat. An optimization model has thus been used to determine the optimal locations for such plants in Sweden. The entire energy supply and demand chain from biomass outtake to gas stations filling is included in the

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optimization. Input parameters have been studied for their influence on both the final ethanol cost and the optimal locations of the plants. The results show that the biomass cost, biomass availability and district heating price are crucial for the positioning of the plant and the ethanol to be competitive against imported ethanol. The optimal location to set up polygeneration plants is demonstrated to be in areas where the biomass cost is competitive and in the vicinity of small to medium size cities. Carbon tax does not influence the ethanol cost, but solicits the production of ethanol in Sweden, and changed thus the geography of the location of the plants. The findings presented in this paper show the optimal locations to build polygeneration plants in Sweden, and also the strength in combining detailed process models included with the entire energy supply and demand chain.

Keywords: bio-ethanol; forestry; optimization; polygeneration; biorefinery

1. Introduction

In March 2007 EU heads of state and governments broadly endorsed the Commission's proposals of a common European energy and climate policy – known as the 20-20-20 Rule referring to 20% less greenhouse gas emissions compared to the 1990 level, a 20% renewable energy share of the total primary energy supply, 20% energy efficiency improvement and finally a 10% biofuel for inland transport target by the year 2020. These policies need to be translated to national action plans. Mainly by mixing gasoline with 5% ethanol, Sweden reached the previous EU goal of 2% biomass derived fuels (biofuels) in the transport sector in 2005. Ethanol will play an important role in reaching the up-coming goals of 5.75% and 10% renewable in the transportation sector by the years 2010 and 2020 respectively. It is important that the ethanol is produced from raw materials that do not compete with food production.

The feedstock should preferably be locally produced as the international competition may increase import prices. Currently, ethanol is mainly imported into Sweden and the commercial ethanol production is limited to feedstock such as wheat and white liquor, but it has been shown that lignocellulosic biomass has a higher energy yield than conventional feedstock for ethanol production [1].

Lignocellulosic ethanol production is one promising technology for future sustainable fuel for the transport sector. Many previous studies have mainly focused on the ethanol process and aimed at reaching higher ethanol yields and efficiencies; see for example [2-5]. By applying integrated systems with simultaneous production of multiple products (polygeneration) instead of independent production plants, the total efficiency is increased. The idea of the biomass-based polygeneration process is to utilize the biomass efficiently and not only focus on the yield for one product, such as ethanol. By investigating the complete system of simultaneous production of electricity, heat, ethanol and biogas from woody biomass, the performance of the total system is considered.

Utilization of polygeneration processes in energy production is an efficient alternative to conventional energy systems. However, studies of energy systems have to consider biomass cultivation, harvesting, transportation, pre-treatment and distribution as well as the conversion process. Biomass costs are varying depending on where the biomass is grown and transportation of biomass as well as fuels have to be optimized. Thus, locations of such plants represent important factors for sustainable production.

This paper presents optimal locations for polygeneration systems with simultaneous production of electricity, district heating, ethanol and biogas in Sweden with the aim to reduce the total production cost and the environmental impact.

2. Methodology

A detailed process model is used to generate input data for an optimization model and optimal geographic locations for polygeneration plants in Sweden are found using a mixed integer linear programming model [6].

2.1. Ethanol production chain

2.1.1. Biomass Supply

The potential increment of wood in the current forests depends on the net primary production (NPP [t_C/ha/year]) of the region, the forest share of the grid (For [%]) and the grid size (GSize [km^2]). The wood increment per year and grid is calculated in (m^3/year/grid) by:

$$\text{IncrementGrid} = c \cdot \text{NPP} \cdot \text{For} \cdot \text{GSize} \qquad (1)$$

The parameter c [m^3 ha / km^2/t_C/grid] is a factor to convert km^2 to hectare, percentage to share, kg of carbon to m^3 of wood, takes harvesting losses into account and estimate the NPP allocation (stem, leave, root). 1 m^3 of spruce correspond to a mass of 430 kg and 1 kg wood consists of 44% carbon, so 1 m^3 of wood will have around 0.2 t_{carbon}. We assume that 30% of the harvesting losses and 50% of the NPP will be stored into the stem. By making this assumption the factor c has a value of 1,750. Annual NPP was calculated for the years 2000 to 2006, and an average value for this time period has been used. The average potential increment calculated for Sweden by using this method is 5.2 m^3/ha/year.

The potential biomass increment was calculated using the global datasets presented in Table 1.

The wood cost was calculated according to Kindermann, 2006 [10], and includes costs of felling and transportation to the forest road. The wood cost is scaled between a minimum and maximum cost per m^3 depending on the population density, forest share and land cost level of the country. Fig. 1 shows a wood cost scenario calculated for Sweden for areas of a slope class of 0-3 degrees. Six slope classes are considered in this studies (0-3; 3-6; 6-10; 10-15; 15-30; 30-50; >50 degrees).

The average cost of biomass in Sweden is calculated to be 15.16 €/m^3. After adding taxes and other transaction costs, a biomass price between 25 and 37 €/m^3 was reached. The biomass price on the Swedish market at present amounts on average to 27 €/m^3 [11].

2.1.2. Biomass Transportation

Five sets of spatial data were utilized in the study (Table 2). For simplicity, all spatial features within the ports, waterways, roads and railroads datasets were considered equal i.e. no distinction was made between road types or port size etc. In addition, it was assumed that all features present within these datasets were navigable and existing on the ground. This is a fair assumption as these datasets contain fairly coarse-level data and would likely represent major features.

Initially, each dataset in Table 2 was converted to grid format. Each dataset was then converted to a Euclidean distance grid. Euclidean distance is calculated from the center of the source cells to the center of each of the surrounding cells. Then this distance was converted to actual distance on the earth surface, geographic coordinates were added to the cell center, and resultant database was created. A final grid resolution of 0.5° (~50km) was chosen.

Biomass and biofuel transportation costs (in €/TJ) are described by Börjesson and Gustavsson [15]. These costs are presented in Table 3, for tractor-trailer, truck, train and boat transportation.

2.1.3. Ethanol Production and Process Integration

Ethanol is traditionally produced from corn in the USA and from sugarcane in Brazil [16]. The major difference between using these two feedstocks for ethanol production is that after pre-treatment, corn must be hydrolyzed before the fermentation, while sugarcane can be fermented directly. After the fermentation, the ethanol is separated by distillation and further dehydrated to the applicable vehicle fuel.

Lignocellulosic biomass can be used as feedstock for ethanol production after pre-treatment and hydrolysis to fermentable sugars. The lignin in the wood is loosened in the pre-treatment and separated after hydrolysis or fermentation depending on the configuration used. The cellulose and hemicellulose is pre-treated with acid, dilute acid or enzyme hydrolysis to sugars of which the 6-carbon (C-6) sugars, mainly glucose, can be fermented with regular baker's yeast. The 5-carbon (C-5) sugars, mainly xylose, requires specially selected or genetically modified micro-organisms for fermentation [17]. The separated lignin can be used as a high quality combustion fuel with a lower heating value of 22.8 MJ/kg at 4.4% moisture content [18].

Several steps in the ethanol process require energy inputs in different forms, and several by-products as output from the process have to be considered in order to reach an efficient system. Thus, the simultaneous production of heat and power in combined heat and power (CHP) plants are suitable for integration with an ethanol production process due to its similar temperatures, pressures and useful by-products. Steam at different pressures is needed for hydrolysis and distillation of ethanol. It is extracted from the steam turbine at appropriate pressures to gain electricity production. Condensed steam discharged from the ethanol production at lower temperatures can potentially be used for district heating production and in other parts of the ethanol production process.

District heating is currently accounting for about 40% of the total heat supply in Sweden [19]. Produced heat in the condensers is the limiting factor for increased electricity production in CHP plants, unless the heat is consumed in cooling towers or other cooling arrangements. Thus, it is also the limiting factor for the production of electricity, ethanol and biogas in a polygeneration system. Since the heat load is limited by the heat demand, it is profitable to reach high power-to-heat ratios.

2.2. Model

2.2.1. Process Model

A steady-state simulation model of a polygeneration system with lignocellulosic ethanol and CHP production has been developed [20], where it is shown that an integrated system can save up to 14% of fuel input compared to a stand-alone CHP and ethanol plant. The model is used to generate input data for the optimization model described in chapter 2.2.2. The configuration is shown in Fig. 2. The model is based on biomass steam CHP technology with a grate-fired boiler and lignocellulosic ethanol production from lab and pilot scale plants. The model is validated with actual operation data from a CHP plant. In Fig. 2, pre-treatment indicates mechanical treatment of the input biomass, and the hydrolysis stage relates to hydrolysis of hemicellulose and cellulose with steam explosion and dilute acid. Steam is extracted from the turbine for hydrolysis and distillation of ethanol, and excess heat from the hydrolysis and distillation is utilized in the district heating system. By-products from the ethanol production, mainly lignin, are combusted in the grate-fired steam boiler.

The process model was simulated and the results in terms of yields of ethanol, electricity, heat and biogas produced from the feedstock were used as input data for the optimization model. Both C5 and C6 sugars are considered to be fermented to ethanol in the model. The dilute acid pre-treatment and separate hydrolysis and fermentation configurations are applied. A sugar yield of 90% will be reached when the technology comes to a commercial stage; a higher yield was then assumed which integrates technology improvements. The yield of hydrolysis has been varied in order to change the yield from wood to ethanol. Two cases with different hydrolysis yields were simulated with the process model at 97% and 90% of theoretical yield of sugars from cellulose and hemicellulose. The lower yield brings less ethanol fuel and biogas production (although higher heat and electricity production) because the unconverted biomass is used for CHP production. The results are shown in Table 4 with different product yields of the polygeneration system.

Economic parameters have been collected to calculate installation and operation costs of the system. A summary of the equipment costs for a polygeneration system with 350 MW of biomass fuel input is shown in Table 5.

Scaling factors in Table 5 are used for up and down scaling of the plant size according to

$$\frac{Cost_a}{Cost_b} = \left(\frac{Size_a}{Size_b}\right)^R \qquad (2)$$

where R is the scaling factor and a and b represent the original plant and the up/down scaled plant respectively. The equipment cost for a circulating fluidized bed (CFB) combustor in Table 5 is used with reference to [21]. A grate-fired boiler has been considered for this study, which might imply less equipment cost than a CFB boiler.

Operational costs for the polygeneration system are summarized in Table 6. Operational costs are mainly taken from [21].

The income from district heating, electricity and biogas are summarized in Table 7. The power price includes electricity certificates as well as the market price.

Transportation costs for produced biogas or electricity are not considered in the model, thus they are assumed to only generate an income at the production site. Electricity is assumed to be sold to the grid and biogas sold at the plant (many city buses and garbage trucks currently run on biogas in Sweden).

2.2.2. Optimization Model

A mixed integer linear programming model [6] is used to optimize the supply and delivery of ethanol. A detailed description of the model is given in Leduc et al., 2008 [27].

In Fig. 3, the model is schematically depicted as a graph with nodes and arcs. A continuous variable is associated to each arc, representing transportation of biomass or ethanol. Binary variables are associated to the plant and gas station nodes, modeling when the current plant or gas station is in operation.

The supply of biomass is restricted in each supply region by the available amount that can be harvested. Plants and gas stations are modeled using energy balance equations, combined with capacity constraints for production or delivery. Depending on whether an ethanol plant is built to produce additional commodities, such as heat and/or power, constraints modeling these specific relations are included. An ethanol demand constraint is defined for each demand region.

The objective is to minimize the overall costs in order to fulfill the demand for ethanol. The cost function that is minimized includes the cost for supply of biomass, operation of production plants, investment in plants and gas stations, handling and delivery of ethanol at the gas stations, and transportation of biomass and ethanol. In this version of the model, the import cost of ethanol is also considered.

Evaluating the model by solving the optimization problem generates the optimal locations, sizes and configurations of production plants. The solution also includes the optimal amount of ethanol that shall be imported, and from which supply region the biomass shall be taken.

2.3. Imports

Gasoline in Sweden is mixed with 85% ethanol (E85). 71% of the 363,000 m^3 ethanol used per year in Sweden is imported [28], mostly from Brazil. This import is also considered in the model. Import from Brazil is transported by boat from Rio de Janeiro to the closest bigger harbor in Sweden, Gothenburg. This represents a distance of 10,536 km [29]. An import price of ethanol to Gothenburg is assumed to be 0.52 €/liter [30]. From here the ethanol can be transported further either by truck, train or boat to fulfill the demand at the most competitive cost. Mixing with gasoline in an intermediate refinery is not considered in this study.

2.4. Scenarios

Input data from the simulated scenarios are summarized in Table 8. About 100 TWh of vehicle fuel is used annually in Sweden, of which about 4% is biofuel [31]. The EU-goal of renewable fuels in the transport sector is 5.75% in 2010 and 10% in 2020 [32]. The biofuel plants studied produce ethanol and other products such as power, heat and biogas. Biogas is here assumed to be used at the plant for local transport (taxis, buses, trucks…) or for other purposes such as heating. It is then not considered in the calculations for the fulfillment of the EU-goals.

The parameters varied in the different scenarios are highlighted in bold letters. The base scenario (scenario 1) is calculated with the prices of 2007 for the biomass, electricity, heat and biogas in Sweden. The influence of the prices of the different products are studied except for the biogas, for which the price is fixed to 18.1 €/MWh [26]. A description on the parameter studied for each set of scenarios is stated in the last column of the table. The heat demand is calculated per person in the populated areas, assuming that the infrastructure for heating systems, such as district heating piping, already exists. Electricity is produced in the polygeneration plants and is distributed to the electricity grid. Connection costs or expansion of the grid to connect to the plants are not considered in the simulations. It is assumed that as much biomass as possible can be used around the new built plant. But taking care of the large amount of biomass used from the other forest industries such as the pulp and paper industry, 30% of the yearly growth of biomass is assumed to be available, which mainly represents forest residues (such as tops and branches) for energy purposes.

3. Results

The results from the scenarios are presented in Table 9. The table presents for each run the number of plants that would be selected and their position number, from 1 to 20 (Fig. 4). The minimum and the maximum costs of ethanol at the gas station are also indicated as well as the total annual amount of imported ethanol.

Fig. 4 presents the identification numbers of the plants selected. The numbers in brackets represent the number of appearance of the corresponding plant. For example, position 15 is selected as an optimal position for three scenarios (scenarios 22, 27 and 28, Table 9).

Scenarios 1-4 are simulated with increasing biomass prices until it is more profitable to import the total ethanol demand from Brazil. Similar scenarios are simulated again with lower income from produced district heating (scenario 5-7) with a lower biomass cost increase to reach 100% import. A decrease of the heat price by 28% would increase the ethanol cost by 75%. An increase of the heat price is studied in scenario 8, where a decrease of the ethanol cost of 26% has been noticed when the heat price increases by 10%.

The changes in ethanol production prices can be studied from scenarios 9 and 10 with changed power prices. A change of the power price by ± 5% would change the ethanol cost by ± 7.5%, without changing the positions of the plants.

Scenarios 11 and 12 are simulated without the existing taxes on the ethanol import. Comparing scenarios 12 and 2 one notices that ethanol would be imported for a biomass cost lower in scenario 12, and one plant less would be needed.

In scenario 13, a carbon tax of 100 €/tonne$_{CO_2}$ on transportation emissions is introduced. A carbon tax on transportation is used together with an increase in biomass costs in scenario 14, resulting in some imports. Comparing scenarios 3 and 14, one notices that three more plants would be needed in the case of a carbon tax, but the final ethanol cost remains unchanged.

Scenarios 15-17 are simulated with varying carbon tax, demand and biomass cost increase to see where the optimal position for the first biorefinery in Sweden should be built by setting the demand to fit the maximum size of one plant. The location chosen for all three scenarios is in the northern part of

Sweden, at longitude 21.75 and latitude 65.75 where biomass costs are lower than average. Scenario 18 is placing one plant of 280 MW in Östersund, at longitude 15.25 and latitude 63.25.

By reducing the amount of available biomass to 5% of the yearly growth and varying the biomass cost increase, it is shown in scenarios 19-21 that the ethanol production cost increases. It increases by an average of 90% and imports would be needed for a biomass cost lower than for scenarios 1-4.

To meet the EU goal of 2020, scenarios 22-26 show that more plants have to be set up.

14 plants are required to meet the ethanol demand with a lower limit for maximum size plants of 200 $MW_{biomass}$ in scenario 27. Scenario 28 shows that with a decreased yield of ethanol and an increased yield of heat and power, four more plants have to be set up to meet the ethanol demand. This scenario however, gives a lower ethanol production price by 80%.

Comparing the scenarios where the biomass cost have changed, one notices that an increase of the biomass price by 20% increases the ethanol cost by an average of 50%.

4. Discussion

Optimal geographic locations of polygeneration plants within Sweden have been presented. The factors that have the most influence on the plant location and ethanol cost are the biomass cost, the biomass availability and the plant efficiencies.

Concerning the by-products, electricity and biogas are assumed to be distributed without constraints; only heat distribution to residential areas would have an impact on the final cost and position of the plant. Thus, in order to generate an income from produced heat for district heating, the plant is best located in populated areas. However, the biomass prices are higher in populated areas which counter this statement. The optimization results show that the optimal locations for the simulated cases are in cities with a range of about 50,000 to 140,000 inhabitants. The optimal size for each plant depends on the heat demand in the region where the plant is located. The regions that were verified to be the most attractive locations include the following cities; Sundsvall, Borlänge, Umeå, Linköping, Östersund, Luleå, Gävle and Växjö.

Apart from the affect of the sold by-products on the ethanol price, the competitive import price has a large impact on whether it is profitable to produce ethanol in polygeneration plants in Sweden. Scenario 11 (ethanol import price of 0.397 €/liter) shows that ethanol production in Sweden with simultaneous electricity, heat and biogas production is still profitable even without import taxes on ethanol from Brazil. However, the operational cost, feedstock cost and other related factors are difficult to predict and it is shown in e.g. scenario 12 that it might be more profitable to import sugarcane-based ethanol than to produce it locally from wood.

Including a carbon tax on the transport and the imported products will not influence the ethanol cost. But as the biomass cost increases the geography of the location of the plants will change. Ethanol produced in Sweden is then solicited.

The ethanol yield reduction in scenario 28 gives the lowest ethanol production cost, which strongly points to the importance of utilizing the by-products of polygeneration rather than producing it separately. The low production cost is due to the income from the increased heat and power yield which clearly shows that the importance of research in this area is not towards optimizing ethanol yield, but instead towards optimizing the energy system as a whole and focusing on the best utilization method of biomass instead of only one product.

The results presented in this paper are especially important for energy policy development and shows that import taxes can promote the technology development needed to stimulate local ethanol production in countries like Sweden.

5. Conclusions

Polygeneration systems with simultaneous production of heat, power, ethanol and biogas utilize the biomass feedstock to a higher extent than in independent production plants. This paper has presented the optimal locations of biomass based ethanol plants with polygeneration in Sweden. With variations of different parameters in the optimization, locations that prove to be optimal were identified and the final ethanol cost calculated.

The biomass cost, biomass availability and the income for by-products such as heat, have a large impact on both the final ethanol costs and the optimal geographic locations. An increase of the biomass cost by 20% increases the ethanol cost by an average of 50%, a decrease of the biomass available by 25% would increase the ethanol cost by 90%, a heat price increase by about 10% decreases the ethanol cost by 25%. The carbon tax has on the other hand very little influence on the ethanol cost but a higher impact on the location of the plants, encouraging limitation on the import of ethanol.

The optimal location for a polygeneration plant would be in the vicinity of cities with a range of about 50,000 to 140,000 inhabitants. In a broader perspective it can be concluded that polygeneration production plants should not be positioned in too dense nor too sparse populated areas, and that Sweden has the opportunity to develop a sustainable ethanol production industry towards the EU goals.

The findings presented in this paper are essential for energy planning purposes on a national and international level.

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7. References

[1] Sims REH, Hastings A, Schlamadinger B, Taylor G, Smith P. Energy crops: current status and future prospects. Global Change Biology 2006;12:2054-76.

[2] Aden A, Ruth M, Ibsen K, Jechura J, Neeves K, Sheehan J, et al. Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover. NREL/TP-510-32438, National Renewable Energy Lab., Golden, CO. (US); 2002.

[3] Sassner P, Galbe M, Zacchi G. Bioethanol production based on simultaneous saccharification and fermentation of steam-pretreated Salix at high dry-matter content. Enzyme and Microbial Technology 2006;39:756-62.

[4] Sun Y, Cheng J. Hydrolysis of lignocellulosic materials for ethanol production: a review. Bioresource Technology 2002;83:1-11.

[5] Öhgren K, Rudolf A, Galbe M, Zacchi G. Fuel ethanol production from steam-pretreated corn stover using SSF at higher dry matter content. Biomass & Bioenergy 2006;30:863-9.

[6] Wolsey L. Integer programming: Wiley-Interscience New York, NY, USA; 1998.

[7] Running S, Nemani R, Heinsch F, Zhao M, Reeves M, Hashimoto H. A continuous satellite-derived measure of global terrestrial primary production. BioScience 2004;54:547-60.

[8] JRC. The Global Land Cover Map for the Year 2000. 2003, p. GLC2000 database, European Commision Joint Research Centre.

[9] Center for International Earth Science Information Network (CIESIN) CUaCIdATC, URL. 2005, p. Gridded Population of the World Version 3 (GPWv): Land Area Grids. Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University.

[10] Kindermann GE, Obersteiner M, Rametsteiner E, McCallum I. Predicting the deforestation-trend under different carbon-prices. Carbon Balance and Management 2006;1.

[11] STEM. Prisblad för biobränslen, torv m.m. Nr 1/2008. Swedish Energy Agency, Eskilstuna, Sweden; 2008.

[12] ESRI. 2008.

[13] General Dynamics Advanced Information Systems. 2008.

[14] Digital Chart of the World Data Server. 2008.

[15] Börjesson P, Gustavsson L. Regional production and utilization of biomass in Sweden. Energy 1996;21:747-64.

[16] Wheals A, Basso L, Alves D, Amorim H. Fuel ethanol after 25 years. Trends in Biotechnology 1999;17:482-7.

[17] Reith J, Veenkamp J, Van Ree R, De Laat W, Niessen J, De Jong E, et al. Co-production of bio-ethanol, electricity and heat from biomass wastes: potential and R&D issues. First European Conference on Agriculture & Renewable Energy. Amsterdam, the Netherlands; 2001, p. 6–8.

[18] Eriksson G, Kjellström B, Lundqvist B, Paulrud S. Combustion of wood hydrolysis residue in a 150kW powder burner. Fuel 2004;83:1635-41.

[19] Sahlin J, Knutsson D, Ekvall T. Effects of planned expansion of waste incineration in the Swedish district heating systems. Resources, Conservation and Recycling 2004;41:279-92.

[20] Starfelt F, Thorin E, Dotzauer E, Yan J. Performance Evaluation of Adding Ethanol Production into an Existing Combined Heat and Power Plant. Biomass & Bioenergy 2008.

[21] Hamelinck C, van Hooijdonk G, Faaij A. Prospects for Ethanol from Lignocellulosic Biomass: Techno-economic Performance as Development Progresses: Utrecht University, Copernicus Institute, Science Technology Society; 2003.

[22] Parsons EL, Shelton WW, Lyons JF. Advanced Fossil Power Systems Comparison Study. NETL USDOE Final Report 2002.

[23] Craig K, Mann M. Cost and Performance Analysis of Biomass-Based Integrated Gasification Combined-Cycle (BIGCC) Power Systems. NREL/TP-43021657 UC Category: 1311-DE96013105 1996.

[24] Nilsholgersson. The Rate Survey "Nils Holgersson" (In Swedish: Avgiftsundersökningen "Nils Holgersson") HSB, Hyresgästföreningen, Riksbyggen, Sabo, Fastighetsägarna; 2008.

[25] Nordpool. Nordpool electricity spot market. 2008.

[26] Kärrman E, Olofsson M, Persson B, Sander A, Aberg H. Food waste disposers – a technical solution for sustainable resource management? A pre-study in Gothenburg (In Swedish: Köksavfallskvarnar – en teknik för uthållig resursanvändning? En förstudie i Göteborg). VA-Forsk; 2001.

[27] Leduc S, Schwab D, Dotzauer E, Schmid E, Obersteiner M. Optimal Location of Wood Gasification Plants for Methanol Production with Heat Recovery. International Journal of Energy Research, IGEC-III special issue 2008.

[28] Lagerkvist Tolke C. Market Overview: Ethanol, a farming and industrial product (In Swedish; Marknadsöversikt: Etanol, en jordbruks- och industriprodukt). Swedish Board of Agriculture; 2006.

[29] maritimeChain.com pte ltd Singapore; 2008.

[30] F.O. Licht's World Ethanol & Biofuels Report. 2007.

[31] Agency SE. Energy use in the tranport sector 2007 (In Swedish: Transportsektorns energianvändning 2007). Eskilstuna, Sweden: Swedish Energy Agency; 2008.

[32] EU. Communication from the Commission – An EU Strategy for Biofuels. In: SEC(2006), editor. 142: Commission of the European Communities; 2006.

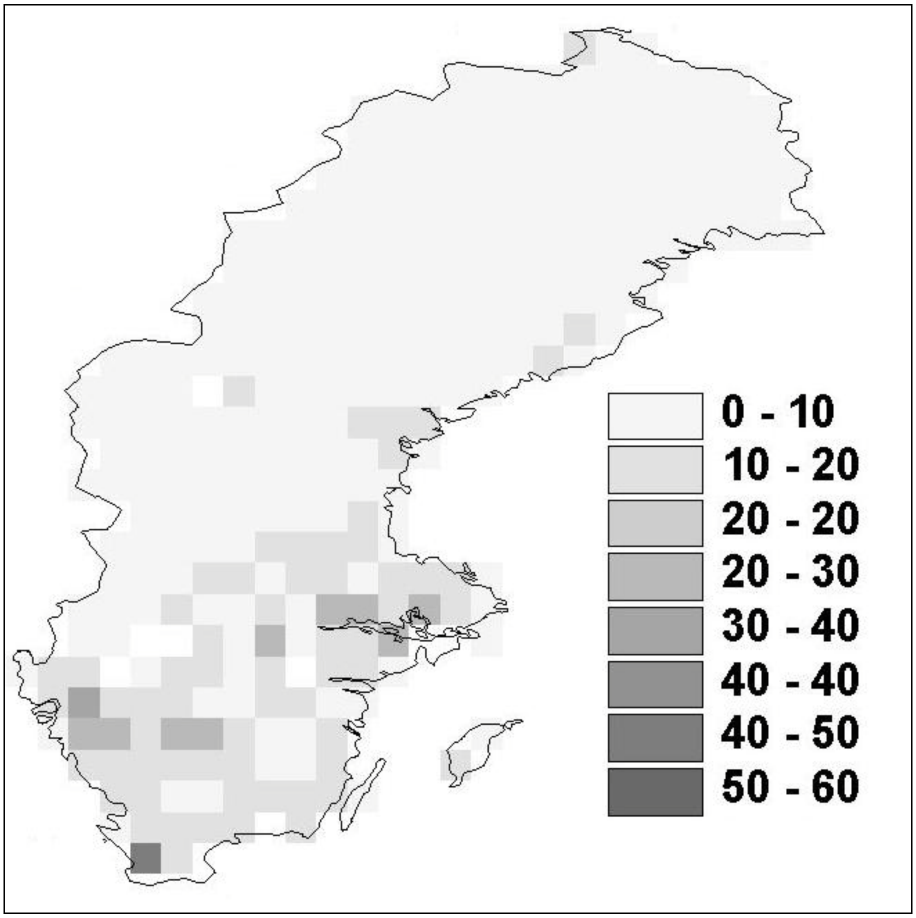

Fig. 1. Wood cost (€/m^3) in Sweden on areas for a slope class of 0-3 degrees.

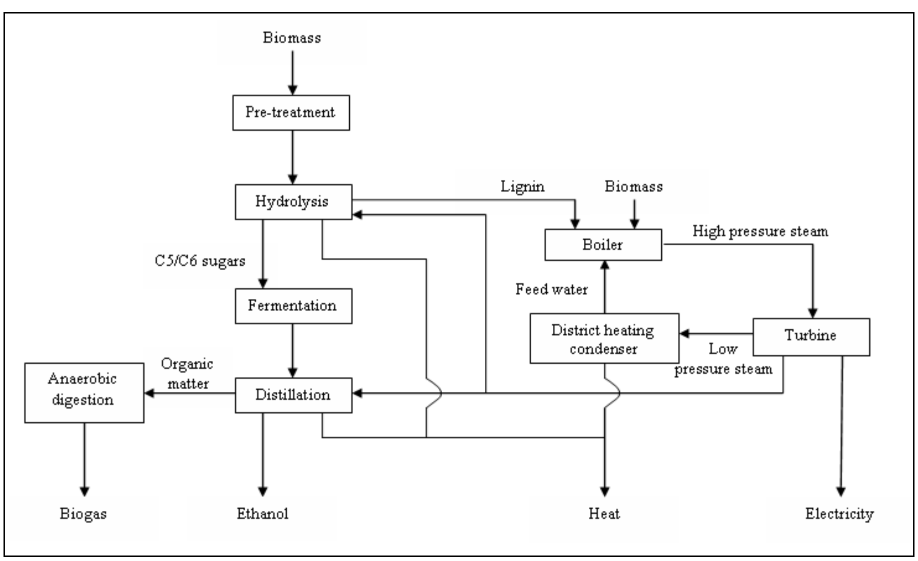

Fig. 2. Configuration scheme of the polygeneration process.

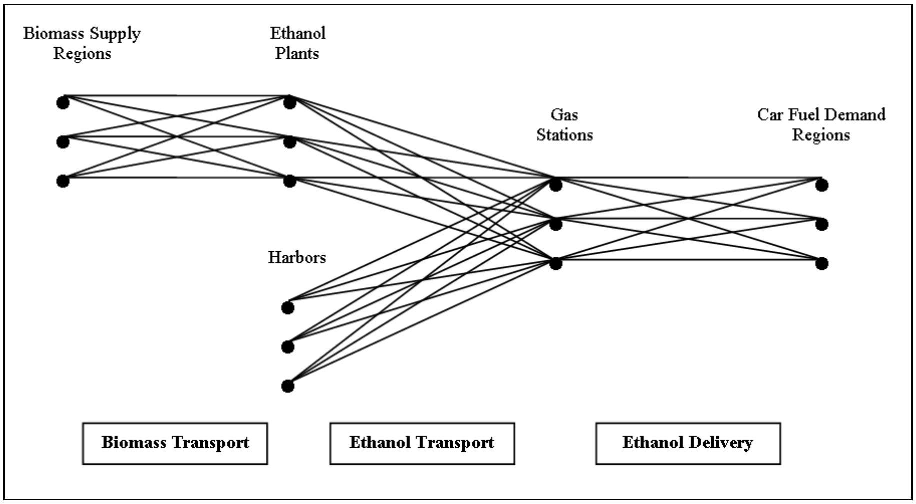

Fig. 3. Scheme of the model.

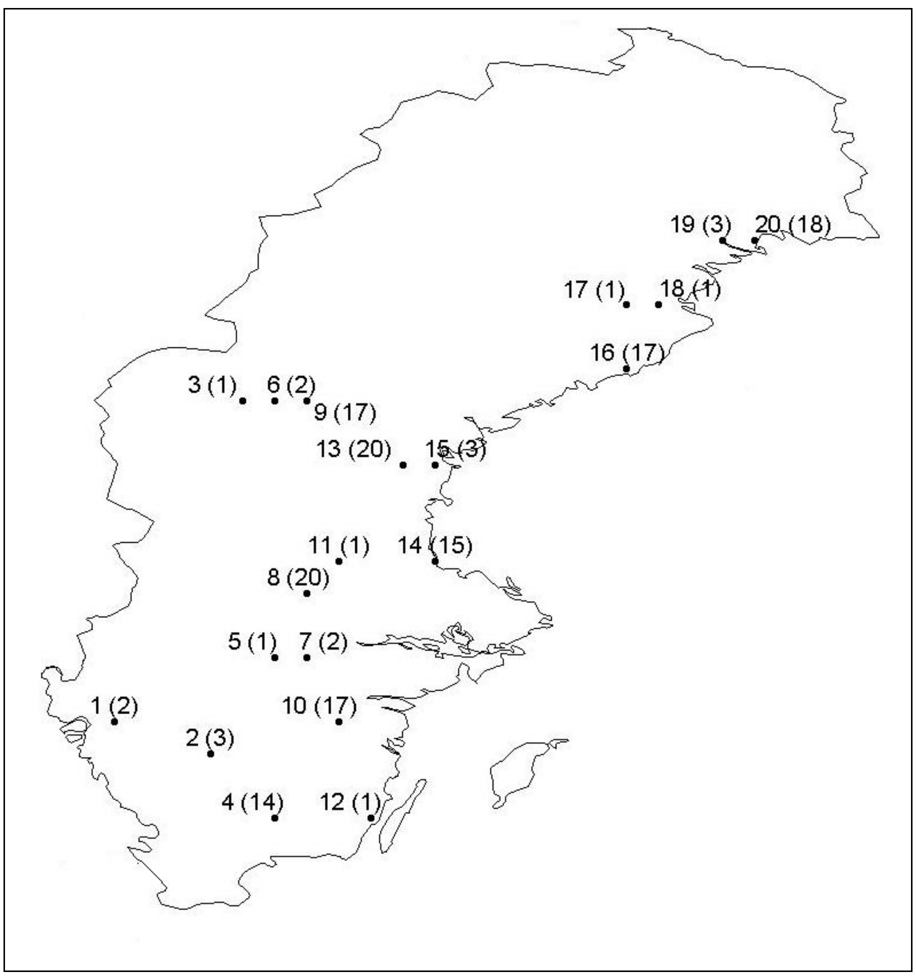

Fig. 4. Plant identification with their number of appearance in brackets.

Table 1

Datasets used for the calculation

Dataset	Value	Source
Net primary production (NPP)	0-25,184 kgC/ha/year	Running et.al, 2004 [7]
Forest share (For)	0-100 %	JRC, 2003 [8]
Grid size (GSize)	0-3,091 km^2	CIESIN, 2005 [9]

Table 2

Description of spatial data utilized in the study

Dataset	Updated	Source
Global maritime ports database	2007	General Dynamics Advanced Information Systems, 2008 [13]
Waterways	2000	ESRI, 2008 [12]
Roads	1993	Digital Chart of the World Data Server, 2008[14]
Railroads	1993	Digital Chart of the World Data Server, 2008[14]

Table 3

Transport costs for logging residues and ethanol in €/TJ regarding different transport alternatives. The transport distance d is in km [15]

Fuel	Tractor	Truck	Train	Boat
Logging residues	226+12.78 d	344+7.77 d	727+1.08 d	836+0.44 d
Ethanol	-	138+3.05 d	423+0.66 d	462+0.15 d

Table 4

Yields for different products calculated from the process model

Hydrolysis yield cases	Fuel	Power	Biogas	Heat
0.97	0.292	0.127	0.183	0.234
0.90	0.258	0.145	0.161	0.277

Table 5

Equipment cost for the polygeneration system [21]

Component	Scaling factor	Investment cost (M€)	Installation factor
Pre-treatment			
Mechanical	0.67	4.44	2.00
Mill	0.70	0.91	1.00
Dilute acid	0.78	14.10	2.36
Steam explosion	0.78	1.41	2.36
Ion-exchange	0.33	2.39	1.88
Overliming	0.46	0.77	2.04
Hydrolysis + fermentation			
Seed fermentors	0.60	0.68	2.20
C5 fermentation	0.80	6.39	1.88
Hydrolyse-fermentation	0.80	6.39	1.88
Upgrading			
Distillation and purification	0.70	2.11	2.75
Molecular sieve	0.70	2.80	1.00
Residuals			
Solids separation	0.65	1.78	2.20
Anaerobic digestion	0.60	2.51	1.95
Power Island			
Boiler	0.73	53.95	2.20
Steam system + turbine	0.70	74.74	1.86

Table 6

Operational costs for the polygeneration system [22, 23]

Capital required	Description
Total Plant Cost (TPC)	
Engineering fee	10% of Process plant cost (PPC)
Process contingency	2.345% of PPC
General plant facilities	10% PPC
Project contingency	15% of (PPC + General plant facilities)
Total Plant Investment (TPI)	
Adjustment for interest and inflation	0.34% PPC
Total Capital Requirement (TCR)	
Prepaid royalties	0.5% of PPC
Start-up costs	2.7% TPI
Spare parts	0.5% of TPC
Working capital	3% TPI
Land, 200 acres	200 Acres at 6,500 € per Acre

Table 7

Energy prices employed in the polygeneration model (Euro/MWh)

Heat price	Power price	Biogas price
69.3 [24]	71.4 [25]	18.12 [26]

Table 8

List of scenarios

Scenarios	Carbon tax	Demand	Ethanol yield	Power yield	Biogas yield	Heat yield	Available biomass	Average biomass price	Ethanol Import price	Heat price	Power price	Max size	Description
	€/t_{CO2}	TWh					%	€/m^3	€/liter	€/MWh	€/MWh	MW_{bio}	
1	0	5.75	0.292	0.127	0.183	0.234	30	25	0.52	69.28	71.41	400	Base scenario
2	0	5.75	0.292	0.127	0.183	0.234	30	**30**	0.52	69.28	71.41	400	Influence on biomass cost
3	0	5.75	0.292	0.127	0.183	0.234	30	**35**	0.52	69.28	71.41	400	
4	0	5.75	0.292	0.127	0.183	0.234	30	**37**	0.52	69.28	71.41	400	
5	0	5.75	0.292	0.127	0.183	0.234	30	25	0.52	**50**	71.41	400	Decrease of heat price
6	0	5.75	0.292	0.127	0.183	0.234	30	**30**	0.52	**50**	71.41	400	
7	0	5.75	0.292	0.127	0.183	0.234	30	**35**	0.52	**50**	71.41	400	
8	0	5.75	0.292	0.127	0.183	0.234	30	25	0.52	**76.23**	71.41	400	Increase of heat price
9	0	5.75	0.292	0.127	0.183	0.234	30	25	0.52	69.28	**67.83**	400	Increase of power price
10	0	5.75	0.292	0.127	0.183	0.234	30	25	0.52	69.28	**74.97**	400	Decrease of power price
11	0	5.75	0.292	0.127	0.183	0.234	30	25	**0.397**	69.28	71.41	400	No tax on imports
12	0	5.75	0.292	0.127	0.183	0.234	30	**30**	**0.397**	69.28	71.41	400	
13	**100**	5.75	0.292	0.127	0.183	0.234	30	25	0.52	69.28	71.41	400	Carbon tax influence
14	**100**	5.75	0.292	0.127	0.183	0.234	30	**35**	0.52	69.28	71.41	400	
15	**100**	**0.59**	0.292	0.127	0.183	0.234	30	25	0.52	69.28	71.41	400	One plant is built
16	0	**0.59**	0.292	0.127	0.183	0.234	30	25	0.52	69.28	71.41	400	
17	0	**0.59**	0.292	0.127	0.183	0.234	30	**30**	0.52	69.28	71.41	400	
18	0	5.75	0.292	0.127	0.183	0.234	30	25	0.52	69.28	71.41	**280**	
19	0	5.75	0.292	0.127	0.183	0.234	**5**	25	0.52	69.28	71.41	400	Available biomass decrease
20	0	5.75	0.292	0.127	0.183	0.234	**5**	**30**	0.52	69.28	71.41	400	
21	0	5.75	0.292	0.127	0.183	0.234	**5**	**35**	0.52	69.28	71.41	400	
22	0	**10**	0.292	0.127	0.183	0.234	30	25	0.52	69.28	71.41	400	Demand increase to year 2020
23	0	**10**	0.292	0.127	0.183	0.234	30	**30**	0.52	69.28	71.41	400	
24	0	**10**	0.292	0.127	0.183	0.234	30	**35**	0.52	69.28	71.41	400	
25	0	**10**	0.292	0.127	0.183	0.234	30	**30**	**0.397**	69.28	71.41	400	2020 goal & no tax on imports
26	0	**10**	0.292	0.127	0.183	0.234	30	**35**	**0.397**	69.28	71.41	400	
27	0	5.75	0.292	0.127	0.183	0.234	30	25	0.52	69.28	71.41	**200**	Maximum size limited
28	0	5.75	**0.258**	**0.145**	**0.161**	**0.277**	30	25	0.52	69.28	71.41	400	Yields change

Table 9

Results for each scenario

Scenarios	Number of plants	Identification numbers of the selected plants (Fig. 4)	Cost min	Cost max	Import
			€/liter	€/liter	m^3/year
1	8	4, 8, 9, 10, 13, 14, 16, 20	0.0650	0.2517	0
2	8	4, 8, 9, 10, 13, 14, 16, 20	0.1164	0.3031	0
3	3	8, 13, 20	0.1577	0.4505	745,218
4	0	-	-	-	1,159,404
5	8	4, 8, 9, 10, 13, 14, 16, 20	0.1433	0.3205	0
6	8	4, 8, 9, 10, 13, 14, 16, 20	0.1947	0.3719	0
7	0	-	-	-	1,159,404
8	8	4, 8, 9, 10, 13, 14, 16, 20	0.0374	0.2302	0
9	8	4, 8, 9, 10, 13, 14, 16, 20	0.0726	0.2593	0
10	8	4, 8, 9, 10, 13, 14, 16, 20	0.0572	0.2439	0
11	8	4, 8, 9, 10, 13, 14, 16, 20	0.0650	0.2517	0
12	7	8, 9, 10, 13, 14, 16, 20	0.1116	0.3336	187,926
13	8	4, 8, 9, 10, 13, 14, 16, 20	0.0650	0.2517	0
14	6	8, 9, 10, 13, 16, 20	0.1600	0.4505	332,211
15	1	19	-	0.2181	0
16	1	19	-	0.2181	0
17	1	19	-	0.3502	15,276
18	1	9	-	0.0879	1,040,707
19	6	2, 3, 8, 10, 13, 16	0.1607	0.4266	536,925
20	4	4, 8, 13, 16	0.2356	0.4395	801,456
21	0	-	-	-	1,159,404
22	13	1, 2, 4, 6, 7, 8, 9, 10, 13, 14, 15, 16, 20	0.0596	0.2351	0
23	8	4, 8, 9, 10, 13, 14, 16, 20	0.1164	0.4047	0
24	3	8, 13, 20	0.1544	0.4275	745,218
25	7	8, 9, 10, 13, 14, 16, 20	0.0920	0.2973	187,926
26	0	-	-	-	2,016,355
27	14	4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15, 17, 18, 20	0.0684	0.1807	0
28	12	1, 2, 4, 7, 8, 9, 10, 13, 14, 15, 16, 20	-0.0174	0.1602	249,713

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Location of a biomass based methanol production plant: A dynamic problem in northern Sweden

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ABSTRACT

Concerning production and use of biofuels, mismatch between the locations of feedstock and the biofuel consumer may lead to high transportation costs and negative environmental impact. In order to minimize these consequences, it is important to locate the production plant at an appropriate location. In this paper, a case study of the county of Norrbotten in northern Sweden is presented with the purpose to illustrate how an optimization model could be used to assess a proper location for a biomass based methanol production plant. The production of lignocellulosic based methanol via gasification has been chosen, as methanol seems to be one promising alternative to replace fossil gasoline as an automotive fuel and Norrbotten has abundant resources of woody biomass. If methanol would be produced in a stand-alone production plant in the county, the cost for transportation of the feedstock as well as the produced methanol would have great impact on the final cost depending on where the methanol plant is located. Three different production plant sizes have been considered in the study, 100, 200 and 400 MW (biomass fuel input), respectively. When assessing a proper location for this kind of plant, it is important to also consider the future motor fuel demand as well as to identify a heat sink for the residual heat. In this study, four different automotive fuel- and district heating demand scenarios have been created until the year 2025. The results show that methanol can be produced at a maximum cost of 0.48 €/l without heat sales. By selling the residual heat as district heating, the methanol production cost per liter fuel may decrease by up to 10% when the plant is located close to an area with high annual heat demand.

1. Introduction

The greenhouse gas emissions from the transport sector represent a large share of the current total anthropogenic emissions, of which road transport is expected to be the largest by 2050 [1]. An increased utilization of bioenergy constitutes one of the key alternatives to replace fossil fuels and mitigate greenhouse gas emissions. At present, different routes for biomass based heat and power production are established in a variety of markets, but only a small amount of liquid biofuels is produced.

Substituting fossil fuels in the transportation sector does not only serve the purpose to mitigate the climate impact, but also to decrease the oil dependency and thereby increase the energy supply security. The global transport sector is today highly dependent on fossil fuels and the introduction of biofuels is an important measure to reduce the CO_2 emissions in this sector. The European Commission has set a target that renewable energies should constitute 5.75% of the sold volume of transport fuels in Europe by the year 2010 [2] and 10% by the year 2020 [3].

Using wood as a primary resource in the transportation sector is a competitive alternative in terms of efficiency, CO_2 mitigation and land requirement [4]. Biomass based methanol appears to be a potential competitor to fossil fuel in the transportation sector, primarily to replace gasoline. Methanol burns at a lower temperature than gasoline, and is less volatile, reducing the risk of explosion or flash fire. Methanol is less flammable than usual gasoline, and methanol fires can be extinguished with water. It also has the advantage of having a greater octane number (107) than gasoline (98). It can also be safely transported by road, rail, barge, ocean tanker or in pipelines. Methanol is also a hydrogen carrier. The main drawbacks using methanol as transportation fuel is that it is a highly toxic substance and that there are concerns about emissions of formaldehyde from methanol-fueled vehicles. Additionally, methanol has lower volumetric energy content than gasoline.

The costs for the feedstock, the feedstock transportation, the methanol production and the methanol transportation represent approximately 26%, 16%, 46% and 12% of the total production cost

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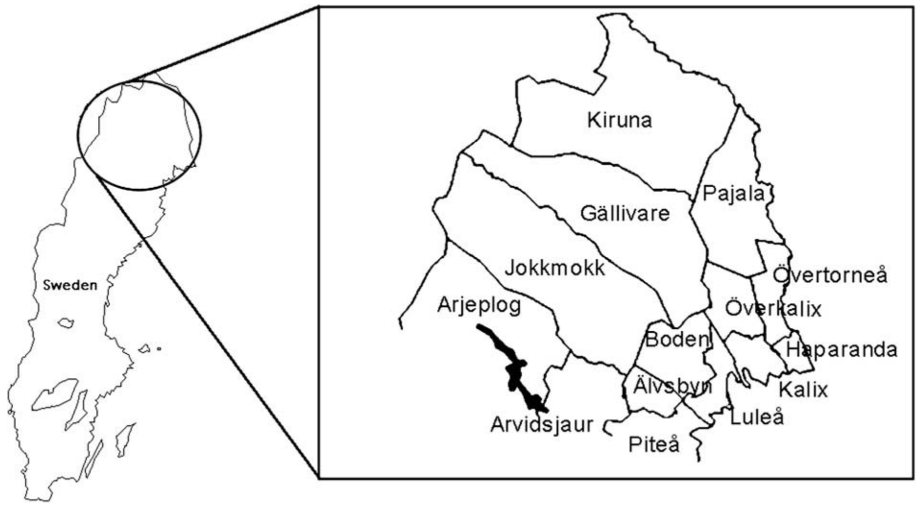

Fig. 1. Maps over the county of Norrbotten subdivided in different municipalities.

respectively; if only truck transportation is considered for a 100 $MW_{biomass}$ plant [5]. These cost shares may differ significantly depending on where the methanol plant is located relative to the feedstock and the gas stations. It is therefore of great importance to build the plants at proper locations and in appropriate sizes to minimize the transportation cost and thereby also reduce the total production cost.

The main objective of this study has been to illustrate the use of a dynamic optimization model in order to find an appropriate geographic position of a methanol production plant to minimize the specific biofuel production cost. The county of Norrbotten in northern Sweden (Fig. 1), where distances between the major cities and the raw material play an important role, has been used as a case study.

2. Methodology

To be able to minimize the transportation cost of feedstock and the produced fuel, it is crucial to know the available amount and location of the feedstock as well as the local automotive fuel demand. To decrease the specific production cost further, it is also important to identify nearby heat sinks to make the residual heat possible to sell either as district heating to nearby societies or as process heat to other industries. The demands for district heating and automotive fuels change over time, which makes it necessary to also consider the possible future development.

In the case study, four different scenarios on how the demands for district heating and motor fuels may develop until the year 2025 have been created for the county of Norrbotten. Additionally, the future forest fuel resources have been assessed. Three different production plant sizes have been considered in the study, 100, 200 and 400 MW (biomass fuel input), respectively (100 MW fuel input means a methanol production of about 90,000 m^3 annually and a biomass supply of about 700 ton per day roughly corresponding to 100,000 ha of land on annual basis).

2.1. Automotive fuel demand

The future development of the automotive fuel demand is strongly depending on demographic changes, changes in car travel habits, infrastructure as well as the technological development of the cars, in particular the fuel efficiencies of the engines. The total transportation fuel demand (E_{fuel}) has been assessed according to Eq. (1):

$$E_{fuel} = P \cdot l_c \cdot c_p \cdot e_d \tag{1}$$

where P represents the total population, l_c is the average driving distance in km per car and year, c_p is the number of cars per capita, and e_d is the specific average fuel consumption (kWh/km).

As an approach to assess the future motor fuel demand, four plausible scenarios for fourteen municipalities in the county have been created. Two different population scenarios titled A and B (created by use of a population projection model, PDE – Population-Development-Environment) [6] constitute the base of the four demand scenarios titled A-BAU, B-BAU, A-Green and B-Green. In the A scenarios, the current demographic trends (fertility rate, mortality, net immigration) of Norrbotten continues, which leads to a declining population, from the current level of 251,000 to 215,000 in the year 2025. The B scenarios represents a brighter future, where the population number approximately stabilizes at the current level.

In the BAU (business-as-usual) scenarios, all the considered parameters (see Eq. (1)) that influence the fuel demand have been extrapolated until the year 2025. In the Green scenario, it is assumed that we work less and thereby also make less business trips. Better interactive communication options facilitate distance work meetings as well as the possibility to work from home which reduces the travelling needs for working purposes. As the spare time increases, there is however more time for leisure travelling. Therefore, it is assumed that the present annual driving distance per car remains at the same level until the year 2025.

The development of the influencing parameters have been assessed through literature studies in combination with own assumptions. Table 1 shows the current and future parameter values in each of the municipalities.

According to the European Commission, renewable sources are to account for 20% of the total energy consumption within the EU, of which biofuels should account for at least 10% of the motor fuel consumption by the year 2020 [7]. Partly due to the abundant resources of biomass in the county of Norrbotten, an even more challenging target of 20% biofuels was set in the BAU scenarios. Assuming that the same required growth rate to reach that target continues, the biofuel demand in the year 2025 becomes 27%. Regarding the development of the gasoline and diesel share, the BAU scenarios assume that the present trends continue, which leads to that the gasoline- and fossil diesel shares amount to 51% and 22%, respectively. The Green scenarios assume that biofuels constitutes as much as 75% of the total demand. Regarding gasoline

Table 1
Current and assumed future average values of the influencing parameters in Norrbotten.

	Current situation (2004)	BAU scenarios (2025)	Green scenarios (2025)
Driving distance (km per car and year)	14,800	17,490	14,800
Car ownership (cars per person)	0.53	0.62	0.50
Average gasoline/diesel consumption (litres per 100 km)[a]	8.6/6.8	7.5/5.5	4.2/3.4

[a] Specific biofuel consumption is assumed to be 30% higher on volume basis than gasoline.

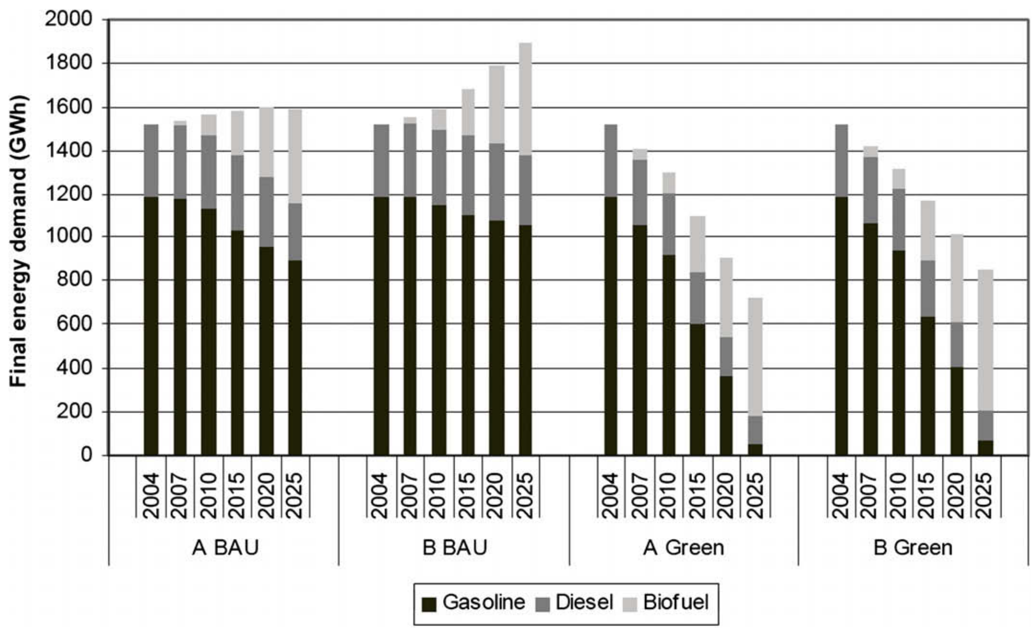

Fig. 2. Total fuel demand for private transport by car in Norrbotten until the year 2025 according to the four scenarios.

and diesel, the shares in the year 2025 is assumed to be 8% and 17%, respectively.

The biofuel may be blended with gasoline before delivery to the gas stations. This is taken into account when the demand levels for the different fuels are calculated. A more detailed description of the methodology and the made assumptions are described by Lundgren and Pettersson [6].

Fig. 2 describes the total fuel demand as well as the assumed evolution of the fuel shares (gasoline, diesel and biofuel) from the year 2004 to 2025. As seen in the figure, the two reference scenarios (BAU) show an increasing motor fuel demand, while the alternative ones (Green) show a significant reduction. Based on the assumed shares, the biofuel demand will be in the range of 430–640 GWh (1.55–2.30 PJ) per year in the year 2025 in the county of Norrbotten.

2.2. Methanol production chain

2.2.1. Potential biomass supply

The estimation of the future potential biomass production is based on data from a forest inventory [8], which comprises about 12,000 forest plot measurements arranged in clusters of around nine circular plots (about 0.007 ha each). For each plot, biomass and biomass-growth per hectare of the three most abundant tree species (Norway spruce, Scots pine, and birch) and other deciduous trees are reported. Each plot is representative of a surrounding forest area, which varies in size between plots and is not geographically explicitly defined. These forest inventory data were converted to a geographically explicit grid using the following method: the whole study area was divided into equally sized grid-cells, 10 × 10 km. For each inventory plot and tree species, the representative forest area was assumed to be circular and centered in the location of the plot. The circular forest areas of the plots were then laid over the grid-cells and distributed to the grid-cells covered according to the area covering each grid-cell.

Biomass productivity was estimated for each grid-cell and tree species using the plot data assigned to each cell (2–50 plots per cell), where each data point (plot) was weighted by the forest area it covers in the grid-cell. By fitting the set of biomass, age and biomass-growth data points for each grid-cell to species specific biomass growth functions [9], site productivity and the mean biomass production over time was estimated. In this estimation it was assumed that the forest management (for example thinning intensity) is not changed, and that forest stands are harvested at an age that maximizes harvested biomass over time. The biomass growth functions used in the estimation relate growth to biomass, age, stand density and site productivity and have been parameterized for all included species using an extensive set of yield table data [9]. In this paper a regional biomass price of 35 €/m^3 (0.02 €/kWh) was assumed to be constant for the complete time period, (a sensitivity analysis on the price is performed in Section 4.3). This is the average value of the wood price in northern Sweden from 2002 to 2007 [10].

According to the calculations, the theoretical potential of woody biomass supply would be around 11.5 TWh (41.4 PJ) per year until 2025, which is around 15.7% more than the inventory from the year 2005 [16]. Table 2 shows the future theoretical potential of forest fuels divided into different tree species. Please note that this is the theoretical potential meaning that less will be available and exploited in practice due to economic or technical restrictions.

Table 2
Woody biomass potential 2025 in Norrbotten in TWh/year (PJ/year in parenthesis).

Feedstock	Pine	Spruce	Birch	Deciduous trees
Potential 2025	5.14 (18.50)	2.96 (10.66)	3.11 (11.20)	0.30 (1.08)

2.2.2. Biomass transportation

The biomass transportation cost (in €/TJ) is described by Börjesson and Gustavson [11]. In the county of Norrbotten, only tractor–trailer and truck transportations are considered represented by Eqs. (2) and (3), respectively.

$$C_{\text{Truck}} = 344 + 7.77d \tag{2}$$

$$C_{\text{Tractor}} = 226 + 12.78d \tag{3}$$

The actual distance (in km) to the methanol plant, d, is defined as the direct distance multiplied by the estimated ratio of actual road length to direct distance (this ratio is estimated to an average value of 1.4 for Norrbotten). These values correspond to the transportation costs if the biomass is extracted from the surrounding areas.

2.2.3. Methanol production

Methanol can be produced from biomass via different gasification technologies. The methanol production facilities typically consist of the following steps: fuel pre-treatment, gasification, gas cleaning, reforming of higher hydrocarbons, shift to obtain appropriate H_2:CO ratios, and gas separation for methanol synthesis and purification [12]. A boiler is optional to employ the unconverted gas for heat production (or a turbine for electricity co-production). According to Hamelinck and Faaij [12], only circulating fluidized bed gasifiers are feasible for large-scale fuel gas production. This conclusion is based on an analysis of throughput, cost, complexity and efficiency issues. They have analyzed two types of circulating fluidized bed gasifiers for methanol production: a pressurized direct oxygen fired gasifier and an atmospheric indirectly fired gasifier. The latter type is selected in this study. In this gasifier, ash, char and sand are entrained in the product gas, separated using a cyclone, and sent to a second bed where the char is burned in air to reheat the sand. The heat is transferred between the two beds by circulating the hot sand back to the gasification bed. This allows one to provide heat by burning a part of the fuel, but without oxygen supply as combustion and gasification occur in separate vessels. The gasifier is fired by air and there is no risk of nitrogen dilution or need for oxygen production [12]. In this study, it is assumed that the blending of methanol with gasoline to suitable mixtures, e.g. M85 containing an 85% share of methanol, is performed on site immediately after the methanol production process.

Scale effects strongly influence the unit cost per plant capacity, which decrease with larger plants or equipments (such as boilers, turbines, etc.). This difference can be adjusted by using the scaling function:

$$\frac{Cost_a}{Cost_b} = \left(\frac{Size_a}{Size_b}\right)^R \tag{4}$$

where R is the scaling factor, $Cost_a$ and $Cost_b$ are the costs of equipments for the biofuel plant (a) and (b), respectively, and $Size_a$ and $Size_b$ are the sizes of the biofuel plant (a) and (b), respectively. Using this information it is possible to calculate costs for different processing steps of methanol plants with different sizes. By adding the costs of the separate units, the total investment cost for the new size is determined, and production cost for the current methanol plant size can be calculated. For biomass systems, R is usually between 0.6 and 0.8 [13]. The uncertainty range of such estimates is up to ±30% on investment costs [12].

2.2.4. Methanol transportation

The transport infrastructure in Norrbotten is mainly suitable for trucks all over the county. The costs of methanol transportation by truck are calculated using figures from Börjesson and Gustavson [11]. The transportation cost by truck (in €/TJ_{methanol}) is described in Eq. (5):

$$C_{\text{Truck}} = 138 + 3.05d \tag{5}$$

where d is the direct distance (in km) from the methanol plant to the gas stations multiplied by the estimated ratio of actual road length to direct distance (this ratio is the same as the ratio for the biomass transportation).

2.2.5. Methanol distribution

It is assumed that all gas stations in the county are able to distribute methanol. As methanol today is not widely used in the transportation sector, adaption at the gas stations will be required. The cost for handling methanol at a gas station with a capacity of 125,000 l/month is between 0.20 and 0.24 €/GJ_{methanol}. The costs are assumed to be independent of the station size [14].

2.3. Model

This section formulates the problem as a Facility Location Problem. Solving the problem will result in the optimal locations and sizes of plants and gas stations under the given conditions.

First, let S be the number of biomass supply regions, let P be the number of plants, let G be the number of gas stations, let D the be the number of demand regions, and let Y be the number of years in the planning horizon. Also define the corresponding sets: $\widetilde{S} = \{1,\ldots,S\}, \widetilde{P} = \{1,\ldots,P\}, \widetilde{G} = \{1,\ldots,G\}, \widetilde{D} = \{1,\ldots,D\}$ and $\widetilde{Y} = \{1,\ldots,Y\}$. Besides biofuel, a plant may be constructed to produce one or several additional commodities, e.g. heat, power, pellets or pulp. Let C be the number of additional commodities and define $\widetilde{C} = \{1,\ldots,C\}$ as the corresponding set.

Define the following variables. Let $b_{i,j,y}$ be the amount of biomass delivered from supply region i to plant j in year y, let $x^{bio}_{j,k,y}$ be the amount of biofuel delivered from plant j to the gas station k in year y, and let $x^{bio}_{k,l,y}$ be the amount of biofuel sold at the gas station k to the customers from the demand region l in year y. Let the variable $x^c_{j,y}$ represent the amount of commodity c that is produced at the plant j during year y. The variable $x^{fossil}_{l,y}$ is the amount of fossil fuel sold to costumers from the demand region l year y. The variables $b_{i,j,y}, x^{bio}_{j,k,y}, x^{bio}_{k,l,y}, x^c_{j,y}$ and $x^{fossil}_{l,y}$ are non-negative. Let the binary variables $u_{j,y}$ and $u_{k,y}$, respectively, indicate if the plant j and the gas station k is in operation year y. If $u_{j,y}$ ($u_{k,y}$) is equal to one, then the plant (station) is in operation, otherwise $u_{j,y}$ ($u_{k,y}$) is zero.

The cost for producing biomass in supply region i year y is $c_{i,y}$. The biomass delivered from region i is restricted by

$$\sum_{j=1}^{P} b_{i,j,y} \le \bar{b}_{i,y}, \qquad i \in \widetilde{S}, \quad y \in \widetilde{Y}, \tag{6}$$

where $\bar{b}_{i,y}$ is the available biomass. The cost for transporting biomass from supply region i to plant j is $t_{i,j,y}$.

Plant j is described by the following parameters and equations. The cost for building a plant with maximal biofuel capacity $\bar{x}^{bio}_j$ in year y is $e_{j,y}$, and the cost for producing in the plant is $c_{j,y}$. The biofuel production is thus restricted by

$$\sum_{k=1}^{G} x^{bio}_{j,k,y} \le \bar{x}^{bio}_j u_{j,y}, \qquad j \in \widetilde{P}, \quad y \in \widetilde{Y}. \tag{7}$$

The plant is modeled using an energy balance equation,

$$\eta_j \sum_{i=1}^{S} b_{i,j,y} = \sum_{k=1}^{G} x_{j,k,y}^{bio} + \sum_{c=1}^{C} x_{j,y}^{c}, \qquad j \in \widetilde{P}, \quad y \in \widetilde{Y}, \tag{8}$$

where η_j is the plant efficiency. The relations between the biofuel and the commodities produced are modeled using parameters ρ_j^c, giving

$$x_{j,y}^{c} = \rho_j^c \sum_{k=1}^{G} x_{j,k,y}^{bio}, \qquad j \in \widetilde{P}, \quad c \in \widetilde{C}, \quad y \in \widetilde{Y}. \tag{9}$$

The produced biofuel in plant j is transported to gas station k for the cost $t_{j,k,y}$.

The cost for setting up a gas station k in year y with the capacity $\bar{x}_k^{bio}$ is $e_{k,y}$. The cost for handling biofuel at the station is $c_{k,y}$. Similar to the plant model, also the gas station is modeled using capacity and energy balance equations, i.e.

$$\sum_{l=1}^{D} x_{k,l,y}^{bio} \le \bar{x}_k^{bio} u_{k,y}, \qquad k \in \widetilde{G}, \quad y \in \widetilde{Y}, \tag{10}$$

and

$$\sum_{j=1}^{P} x_{j,k,y}^{bio} = \sum_{l=1}^{D} x_{k,l,y}^{bio}, \qquad k \in \widetilde{G}, \quad y \in \widetilde{Y}, \tag{11}$$

must hold.

The demand for car fuel in region l year y is modeled by

$$\sum_{k=1}^{G} x_{k,l,y}^{bio} + x_{l,y}^{fossil} = d_{l,y}, \qquad l \in \widetilde{D}, \quad y \in \widetilde{Y}, \tag{12}$$

where $d_{l,y}$ is the demand calculated from Eq. (1). The corresponding transportation cost is $t_{k,l,y}$, which shall be interpreted as the driving cost for people driving from region l to gas station k. The fossil fuel is assumed to be available for a price $p_{l,y}^{fossil}$.

In this paper, one additional commodity c, heat, is considered. Therefore, also define the variable $q_{j,y}$ as the heat from an alternative heat source located close to plant j. The heat demand equation is

$$x_{j,y}^{c} + q_{j,y} \ge q_{j,y}^{D}, \qquad j \in \widetilde{P}, \quad y \in \widetilde{Y}, \tag{13}$$

where the parameter $q_{j,y}^{D}$ is the corresponding heat demand. The alternative heat source, which typically is a heating boiler or a CHP plant, is associated with a production cost $c_{j,y}^{heat}$.

Once a plant or a gas station is built, it is available the following years. This is modeled using

$$u_{j,y} \ge u_{j,y-1}, \qquad j \in \widetilde{P}, \quad y \in \widetilde{Y}, \tag{14}$$

and

$$u_{k,y} \ge u_{k,y-1}, \qquad k \in \widetilde{G}, \quad y \in \widetilde{Y}. \tag{15}$$

Given the costs and prices, the objective function is defined as

$$\begin{cases} f(b,x,q,u) = \sum_{y=1}^{Y}\sum_{i=1}^{S}\sum_{j=1}^{P}(c_{i,y}+t_{i,j,y})b_{i,j,y} \\ \quad + \sum_{y=1}^{Y}\sum_{j=1}^{P} e_{j,y}(u_{j,y}-u_{j,y-1}) + \sum_{y=1}^{Y}\sum_{j=1}^{P}\sum_{k=1}^{G}(c_{j,y}+t_{j,k,y})x_{j,k,y}^{bio} \\ \quad + \sum_{y=1}^{Y}\sum_{j=1}^{P} c_{j,y}^{heat} q_{j,y} + \sum_{y=1}^{Y}\sum_{k=1}^{G} e_{k,y}(u_{k,y}-u_{k,y-1}) \\ \quad + \sum_{y=1}^{Y}\sum_{k=1}^{G}\sum_{l=1}^{D}(c_{k,y}+t_{k,l,y})x_{k,l,y}^{bio} + \sum_{y=1}^{Y}\sum_{l=1}^{D} p_{l,y}^{fossil} x_{l,y}^{fossil}. \end{cases} \tag{16}$$

Finally, define the Facility Location Problem as

$$\begin{cases} \min\limits_{b,x,q,u}[f(b,x,q,u)] \\ s.t. \\ (6)-(16) \\ b_{i,j,y}, x_{j,k,y}^{bio}, x_{j,y}^{c}, x_{k,l,y}^{bio}, x_{l,y}^{fossil}, q_{j,y} \ge 0, \quad i \in \widetilde{S}, j \in \widetilde{P}, c \in \widetilde{C}, k \in \widetilde{G}, \\ \quad l \in \widetilde{D}, y \in \widetilde{Y} \\ u_{j,y} \in \{0,1\}, u_{k,y} \in \{0,1\}, \quad j \in \widetilde{P}, k \in \widetilde{G}, y \in \widetilde{Y}. \end{cases} \tag{17}$$

The problem is an ordinary Mixed Integer Program (MIP) and can thus be solved using standard MIP techniques [15].

3. Case study

Norrbotten is the largest county in Sweden covering around 25% of the country's total area. Norrbotten is sparsely populated with an average population density of around 2.5 inhabitants per square kilometer and is strongly characterized by its arctic climate. Norrbotten is also a county with abundant resources of biomass. Currently the total supply of combustible renewable and waste amounts to nearly 6.7 TWh/year (24.12 PJ/year). The annual supply is mainly dominated by black liquor in the paper- and pulp-industries corresponding to roughly 4.0 TWh (14.4 PJ/year). The present share of woody biomass is around 34% corresponding to 2.3 TWh/year (8.28 PJ/year) [16]. Municipal waste contributes with a minor part. At present, the biomass is mainly used in the paper- and pulp-industries, sawmills and district heating plants. No liquid biofuels are currently produced, even if the potential is considered as large. Norrbotten has the particularity that biomass must be supplied from long distances over the county and methanol supplied to concentrated areas around the coastline.

A grid over the county is considered where each grid point is located every third of a degree. The fourteen main cities are also considered in this grid. Each grid point represents a potential position of the plant.

It is assumed that when the local demand is fulfilled, the amount of excess methanol is sent by truck to the main harbor in the city of Luleå from where it can be exported either by train or ship. The study does not consider any export market, and limits the transport of methanol within the county only.

The district heating demand is also considered in the model. Table 3 shows the current heat demand of each municipality in the county with their different heat price. From Table 4 one can find the change in the heat demand for the four scenarios, within the whole county. It is further assumed that the heat demand and price are fluctuating at the same rate all over the county and that exist-

Table 3
Heat demand in GWh/year (PJ/year in parenthesis) from the district heating [19] and heat price [18] in €/kWh for different municipalities in Norrbotten.

Municipality	Heat demand	Heat price
Luleå	690 (2.48)	0.0393
Boden	259 (0.93)	0.0472
Kiruna	209 (0.75)	0.0646
Piteå	175 (0.63)	0.0504
Gällivare	136 (0.49)	0.0642
Kalix	97 (0.35)	0.0630
Haparanda	46 (0.17)	0.0588
Älvsbyn	40 (0.14)	0.0542
Jokkmokk	36 (0.13)	0.0748
Överkalix	26 (0.09)	0.0656
Övertorneå	26 (0.09)	0.0678
Pajala	22 (0.08)	0.0574

Table 4
Change in the heat demand and price in % from 2005 to 2025 for the county.

	2005	2010	2015	2020	2025	References
Heat demand, A-BAU	0	1.3	2.7	4.0	5.3	[6]
Heat demand, A-Green	0	−5.4	−10.9	−16.3	−21.8	[6]
Heat demand, B-BAU	0	5.7	11.5	17.2	23.0	[6]
Heat demand, B-Green	0	−2.2	−4.5	−6.7	−8.9	[6]
Heat price	0	5.5	11.1	11.1	11.1	[17]

ing district heating network can be used without any restrictions. Moreover, it is assumed that 10% of the total fuel input to the plant becomes residual heat that can be sold as district heating within a 30 km radius from the plant.

4. Results and discussion

4.1. Results without district heat production

In all four scenarios described in Fig. 2, a methanol plant would be built in the first year, and all excess of methanol is considered for export. In these cases, no heat is sold to any district heating network. The cost of methanol produced from these plants is in the range of 0.40–0.48 €/l depending on the plant size. In Table 5 the most proper positions, the costs and other details for each plant size are presented for the year 2025.

4.2. Results with district heat production

The specific methanol production cost will change if the residual heat can be sold to an adjacent district heating network. If a 100 $MW_{biomass}$ or a 200 $MW_{biomass}$ plant is built, the optimal position becomes the town of Boden independent of the heat price and demand scenario. The methanol cost decreases by 0.009 €/l as the heat price increases by 0.01 €/kWh (Fig. 3).

If a 400 $MW_{biomass}$ plant is built, the plant location moves towards higher heat demand areas. In this case, the optimal position becomes the town of Luleå. As the 400 $MW_{biomass}$ plant can deliver a larger amount of heat than the two smaller plants, the location is more influenced by the heat price and the heat demand. This shall be set in relation to the costumer price for district heating, which in the county ranges from 0.039 to 0.083 €/kWh [18]. The heat price has the same influence in all scenarios and controls the position of the plant to move closer to the heat demand. However, in Luleå there is a lot of inexpensive excess heat already available from the local steel industry. This issue is analyzed in Section 4.3, as well as other factors that may affect the methanol cost and the plant position.

Table 5
Results for the different scenarios (no district heat production considered), for the year 2025.

Size	$MW_{biomass}$	100	200	400
Position		Boden	Boden	Boden
Load hours	h	7200	7200	7200
Wood				
Amount	t/year	207,360	414,720	829,440
Share of potential	%	6.25	12.5	25
Area	ha	82,030	191,779	407,445
Methanol sold	m^3/year	90,340	180,680	361,350
Max distance				
Biomass transports	km	65	100	170
Fuel transports	km	180	320	340
Costs				
Biomass cost	€/GJ	10.75	10.75	10.75
Biomass transports	€/GJ	1.95	2.33	3.26
Plant cost	€/GJ	17.49	14.09	11.38
Fuel transports	€/GJ	0.38	0.35	0.22
Gas station cost	€/GJ	0.24	0.24	0.24
Total cost				
Mean	€/l	0.48	0.43	0.40

4.3. Sensitivity analysis

A sensitivity analysis is carried out with focus on the following parameters: biomass price, transportation costs, heat prices and heat demand. A change in both the heat price and the transport costs is also studied. Moreover, as Luleå has vast amounts of excess heat available at a low price [18] from the local steel mill, a change of the heat price is also studied by assuming a very low cost for the district heat in Luleå. A base heat price for Luleå in 2005 is assumed to be 0.01 €/kWh, and is presumed to increase until 2025 at the

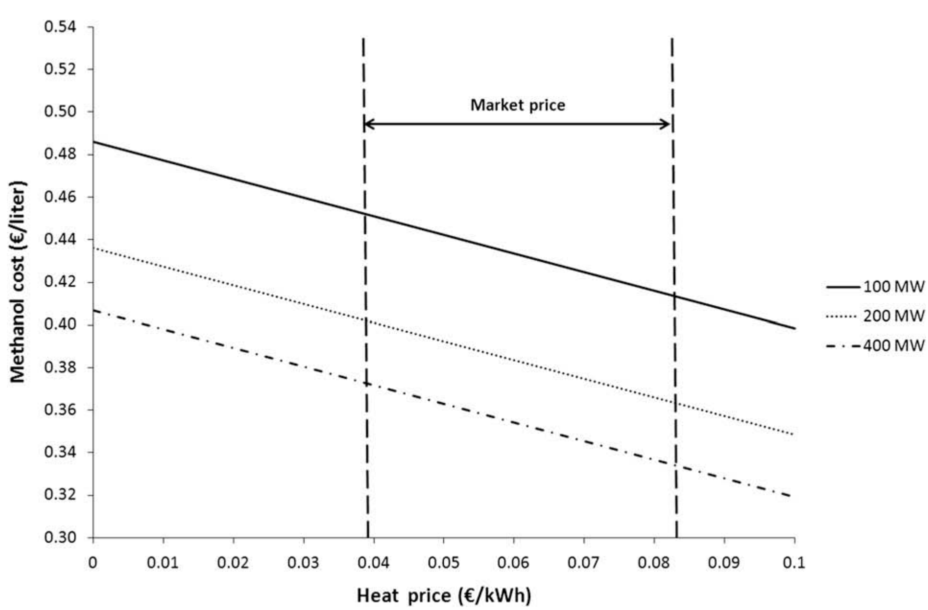

Fig. 3. Influence of the heat price on the methanol cost.

same rate as the heat price in the other municipalities of the county. The influence on the final methanol cost and the plant position from those parameters is analyzed for each plant size and each energy demand scenario. The scenarios studied in the sensitivity analysis are presented in Table 6.

The results are similar for all plant sizes and energy scenarios. Fig. 4 presents the change of the methanol cost in % from 2005 to 2025 compared with the 2005 value for a plant size of 100 $MW_{biomass}$ and the A-BAU scenario. The base scenario presented in Fig. 4 represents the simulation from the Section 4.2 adapted with different heat price for each town.

The parameter that has the most influence on the final methanol production cost is the biomass price. An increase of the biomass price by 54% by 2025 would mean an increase of the methanol production cost by 21%. If the transportation costs increase by 7%, the methanol production cost increases by 1%. Considering the increase of the energy price in general (heat and transport), the methanol cost would then decrease by about 0.5%, and considering only a low heat price in Luleå, the methanol cost would decrease by about 1%.

Considering the positions of the plants, the results are presented in Table 7. For the 100 $MW_{biomass}$ plant, the optimal position would be moved from the town of Boden to Kalix: all the heat produced can indeed be sold at a price in Kalix 33% higher than in Boden, which makes Kalix more attractive for this plant size. For the 200 $MW_{biomass}$ plant, all the heat produced can be sold in Boden. Finally, for the 400 $MW_{biomass}$ plant, all the heat produced can be sold in Luleå at present market price. But considering the very low heat price in Luleå, the location of the plant becomes more interesting in Boden.

Table 7
Position of the plant regarding the size and the energy scenarios.

Plant size ($MW_{biomass}$) Parameters	100 All	200 All	400 All except LHP[a]	400 LHP[a]
A-BAU	Kalix	Boden	Luleå	Boden
A-Green	Kalix	Boden	Luleå	Boden
B-BAU	Kalix	Boden	Luleå	Boden
B-Green	Kalix	Boden	Luleå	Boden

[a] LHP stands for low heat price only in Luleå.

Table 8
Increase radius of the collecting feedstock and fuel distribution and difference in emissions when the plant is relocated from Boden to Luleå.

Plant size, $MW_{biomass}$	Biomass transport, km	Methanol transport, km	Emissions difference per year				
			t_{CO2}	t_{NOx}	t_{PM}	t_{HC}	t_{CO}
400	20	67	2031	19.56	0.43	1.65	3.76

4.4. Influence on emissions

When the plant considers district heat production, the optimal position of the plant will be located closer to the heat demand, which implies changes in distances for the biomass and biofuel transportation. The emissions from the road transports are therefore affected. Table 8 presents the increase of emissions from the transportation of the feedstock and the produced biofuel if a plant is built in Luleå instead of in Boden. This change of position would

Table 6
Parameters used in the sensitivity analysis.

Scenarios	Units	2005	2010	2015	2020	2025	References
Biomass price	€/m^3	36.9	41.8	46.8	51.9	57.0	[17]
Transportation cost	%	0	2.9	5.2	6.3	7.3	[17]
Heat price	%	0	5.5	11.1	11.1	11.1	[17]
Energy price	The sum of transportation costs and heat price						
Low heat price in Luleå	Heat price in Luleå: 0.01 €/kWh Heat price in the rest of the county: unchanged						

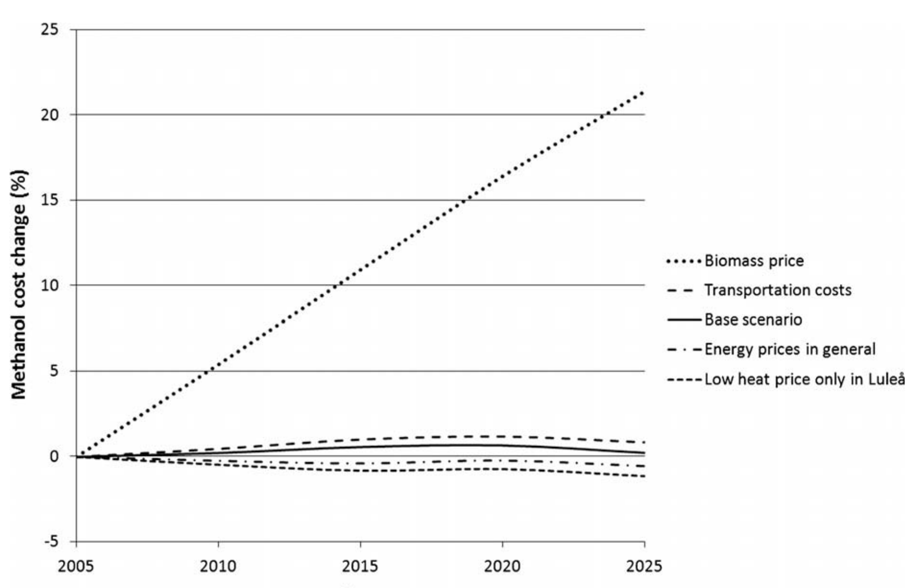

Fig. 4. Results from the sensitivity analysis: the change in percent of the methanol cost for the 100 MW plant and demand scenario A-BAU, from 2005 to 2025 in comparison with the 2005 level.

increase the emissions of CO_2 by 2031 t/year. This represents approximately 0.7% of the total CO_2 emissions from the road traffic in Norrbotten [16]. Emissions of nitrogen oxides (NO_x), particulate matters (PM), hydrocarbons (HC) and carbon monoxide (CO) are also presented in the table.

5. Concluding discussion

The main objective of this study was to illustrate the use of a dynamic model to optimize the geographic position of a biomass based methanol plant by minimizing the transport distances of raw material and the final product, methanol. Also the prerequisite that the plant should be able to sell the residual heat as district heating was taken into account in order to increase the profitability. The study was conducted on a twenty year perspective, for which the future methanol demand was assessed by scenarios and potential biomass supply calculated. The county of Norrbotten in northern Sweden served as a case study, for which appropriate locations of methanol plants of different sizes were computed for four different motor fuel demand scenarios.

The results of the case study show that methanol can be produced in the county of Norrbotten at a maximum specific cost of 0.48 €/l without heat sales. By selling the residual heat as district heating, the methanol production cost per liter fuel may decrease by up to 10% when the plant is located close to an area with high annual heat demand. Therefore, the revenue from heat sales is strongly affecting the location of the plant.

This model can be applied to any kind of biomass based production plant and become an essential tool to optimize the location of new plants on the regional or country level. In particular when long transport distances is an issue for the production cost. The model is therefore a useful tool for decision makers on the level of energy planning purposes. In an international perspective, trades of raw material and biofuels should be implemented. The model could be applied in significantly larger scales (e.g. continents like Europe, North America) to identify the appropriate locations for energy plants to obtain competitive products by minimizing transports and optimizing the use of residual energies. It is also of great importance to have a future time perspective as the feedstock resources as well as the demand for the final products (e.g. heat, motor fuel, electricity) may change radically during the technical and economic lifetime of the plant.

References

[1] Fuglestvedt J, Berntsen T, Myhre G, Rypdal K, Skeie RB. Climate forcing from the transport sectors. Proc Natl Acad Sci USA 2008;105(2):454–8.
[2] Commission of the European Communities. Communication from the commission to the European parliament, the council, the economic and social committee and the committee of the regions on alternative fuels for road transportation and on a set of measures to promote the use of biofuels. COM; 2001. 547p.
[3] Commission of the European Communities. Communication from the Commission to the European Council and the European Parliament, an Energy Policy for Europe. Brussels; 2007.
[4] Bram S, De Ruyck J, Lavric D. Using biomass: a system perturbation analysis. Appl Energy 2009;86:194–201.
[5] Sørensen ÅL. Economies of scale in biomass gasification systems. IIASA, interim report; 2005, IR-05-030.
[6] Lundgren J, Pettersson T. FOCUS – Energy resources in Norrbotten [FOKUS – Norrbottens energiresurser]. Norrbottens energikontor AB (NENET); 2007 [in Swedish].
[7] Swedish Environmental Objectives Council. Sweden's environmental objectives – in an interdependent world. Progress report from the Swedish Environmental Objectives Council; 2007.
[8] The Swedish National Forest Inventory. Department of Forest Resource Management, Swedish University of Agricultural Sciences. <www.riksskogstaxeringen.slu.se> [01.10.07].
[9] Franklin O. Modeling forest production and carbon storage potentials in response to management in the European Union 2005–2050. In: Obersteiner et al, editor. INSEA EU FP 6; 2006. Project SSPI-CT-2003/503614.
[10] Statistical Yearbook of Forestry 2007. Official statistics of Sweden. Jönköping: Swedish Forest Agency; 2007.
[11] Börjesson P, Gustavson L. Regional production and utilization of biomass in Sweden. Energy 1996;21(9):747–64.
[12] Hamelinck CN, Faaij APC. Future prospects for production of methanol and hydrogen from biomass. Utrecht, Netherlands: Utrecht University, Copernicus Institute, Science Technology and Society; 2001.
[13] Tijmensen M, Hooidonk GV. Long term perspectives for production of fuels from biomass; integrated assessment and RD&D priorities – final results. Utrecht, Netherlands: Utrecht University, Copernicus Institute, Science Technology and Society; 2000.
[14] AMF-EA. Engineering. Methanol refueling station costs. Prepared for American methanol foundation. Prepared by EA engineering, science and technology, Inc. Silver Spring. US; 1999.
[15] Wolsey LA. Integer programming. John Wiley and Sons; 1998.
[16] Swedish Statistics. Annual energy balances by region, category, energy carrier and time. <www.h.scb.se/scb/mr/enbal/database/energi/Balanser/Balanser_lan.asp> [15.10.07].
[17] The Swedish Energy Agency, Energimyndigheten. Långsiktsprognos 2006 – Enligt det Nationella Systemet för Klimatrapportering. ER 2007:02; 2007 [in Swedish].
[18] Nils Holgersson. Avgiftsundersökningen, 2007. <www.nilsholgersson.nu/Arkiv.asp> [11.12.08].
[19] Swedish District Heating Association, Statistics 2004, February 2006. <www.svenskfjarrvarme.se> [10.10.07].

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Review

Methanol production by gasification using a geographically explicit model

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ABSTRACT

Methanol mixed with 15% gasoline appears to be a viable alternative energy source for the transportation sector. Produced from gasification of certified wood coming from well-managed forests, its production could be considered as sustainable and the well-to-wheel emissions can be reduced significantly. The physical flows of the entire bio-energy chain consisting of harvesting, biomass transportation, methanol production by gasification, methanol transportation, and methanol distribution to the consumers are assessed and costs are estimated for each part of the chain. A transportation model has been constructed to estimate the logistic demands of biomass supply to the processing plant and to the supply of gas station. The analysis was carried out on a case study for the geography of Baden-Württemberg, Germany. It has been found that a typical optimal size for methanol production of some 130,000 m^3, supplies about 100 gas stations, and the biomass supply requires on average 22,000 ha of short-rotational poplar, with an average transportation distance of biomass of some 50 km to the methanol processing plant. The methanol production costs appear to be most sensitive with respect to methanol plant efficiency, wood cost, and operating hours of the plant. In an area where biomass is spread heterogeneously, apart from the demand, the geographical position of the plant would appear to have a major impact on the final biofuel cost.

1. Introduction

1.1. *Background*

Methanol is the simplest form of alcohol and has the chemical formula CH_3OH. It can be produced chemically from both biomass and fossil fuels. Today, 90% of methanol produced originates from natural gas [1] and represents 37.5 million tones methanol per year [2]. Methanol is suitable as transportation fuel, chemical building block, or as solvent. When used in the transportation sector, methanol can be used either in compression ignited (CI) engines or in fuel cells. For CI engines, it has become a popular choice especially for the Indy cars for its high octane (102) and safety characteristics. Mixed with 15% gasoline (M-85), it can be used for the regular car fleet. This would though require minor modifications on the engines leading to significant environmental benefits due to the reduction of reactive emissions [3] compared to CI engines.

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Concerning fuel cells, methanol may play an important role since it is easier to transport and store than hydrogen [1].

Ahlvik and Brandberg [4] showed that methanol was the fuel that has the highest system efficiency of all liquid fuels from biomass. Methanol is liquid at normal environmental conditions, which makes it easy to handle compared to hydrogen or dimethyl ether (DME). Regarding greenhouse gas (GHG) reduction potentials, biomass-based fuels can have a magnitude of 80–90% [4]. Wahlund et al. [5] compared different alternatives for motor fuels, and concluded that methanol, ethanol or DME appears to give about the same CO_2 reduction. However, when the heat can be used, methanol and DME production give somewhat higher CO_2 reduction than ethanol production.

1.2. *Objectives*

The aim of this study is to analyze the cost of biomass-based methanol on a geographic region and its sensibility to different parameters. Thus the supply chain of biomass-based methanol production and distribution is analyzed. This chain includes biomass harvesting, biomass transportation to the plant, methanol production, methanol transportation to the gas station, and handling of methanol at the gas station. Each system of the supply chain is studied separately and costs are estimated in a consistent manner. This supply chain is applied explicitly to the geographic region of Baden-Württemberg, Germany. A sensitivity analysis is carried out to analyze the most influential parameters of the chain. This analysis is carried out with a factorial design allowing an interpretation of the importance of each parameter in the final methanol cost. This study is mainly built on the energy chain described by Sørensen [7], and the economic data on the methanol production presented by Hamelinck and Faaij [8]. Unless other studies [6] this analysis is based on geographically explicit data, allowing the costs to be closer to expectation. This study would be an introduction tool for geographically explicit energy planning for policy makers.

2. The methanol chain

2.1. *Biomass production*

A methanol processing plant can be supplied by biomass from woody species. Short-rotational poplar coppice provides high potentials for producing biomass in an environmentally benign manner and at relatively low unit costs [9]. In the case of Baden-Württemberg, biomass production of a short-rotational poplar coppice system has been modeled by Schmid et al. [10], using the latest version of the bio-physical process model EPIC [11]. The poplar coppice system is fertilized with nitrogen only in the first two years of each rotation period. Biomass is harvested every six years over a rotation period of 30 years. It is assumed that poplar coppice is planted only on agricultural lands with decent slopes (<5%), because of large harvesting machines to keep harvesting costs per unit competitive. The results on the yields per annum from Schmid et al. [10] have been used in this study.

Although biomass production costs depend on inter alia plant species, type of production system, and land type, the biomass price may have a different value regarding the size of the plant, but as no data were specifically available, a biomass market price was assumed to be constant and equal to $30\,€\,m^{-3}$ for the average set-up [9]. The biomass price depends mainly on the long-term contracts a plant can sign with its supplier. We further assume that the biomass is provided by only short-rotation poplar coppice, and the harvest losses are 25%.

2.2. *Biomass transportation*

The cost of biomass transportation (in $€\,TJ^{-1}$) is described by Börjesson and Gustavson [12], and represented by equations (1) and (2), for tractor-trailer and truck transportation systems, respectively. Although these estimations are from 1996, they are still valid 10 years later, with consideration of a 7% consumption improvement, and 35% consumption increase due to regular stops during transportation [13].

$$C_{\mathrm{Tractor}} = 226 + 12.78d \tag{1}$$

$$C_{\mathrm{Truck}} = 344 + 7.77d \tag{2}$$

The actual distance (in km) to the methanol plant, d, is defined as the direct distance multiplied by the ratio of actual road length to direct distance. These values correspond to the transportation costs when biomass is extracted from the surrounding areas. The ratio of actual road length to direct distance can be between 1 (straight and flat roads) and 3 (mountainous landscape). For Baden-Württemberg, an average value for d of 1.6 has been found.

Under these conditions, a tractor-trailer system is typically the most cost efficient way of transportation up to a distance of 25 km. For longer distances truck transportation becomes cost efficient. Although train and ship are more cost efficient for distances above 50 km, only tractor and truck transportation systems are considered in this study as average transportation distances for plant supply are hardly much longer.

2.3. *Methanol production*

Methanol is assumed to be produced from biomass via gasification. The methanol production facilities typically consist of the following units: Pretreatment, gasification, gas cleaning, reforming of higher hydrocarbons, shift reaction to obtain appropriate H_2:CO ratios, and gas separation for methanol synthesis and purification [8]. The unconverted gases can be used in a gas turbine or boiler and a steam turbine resulting in heat and electricity co-production.

According to Hamelinck and Faaij [8], only circulated fluidized bed gasifiers are suitable for large-scale fuel gas production. Hamelinck and Faaij [8] analyzed two gasifiers for methanol production: a pressurized direct oxygen fired gasifier and an atmospheric indirectly fired gasifier. The later appeared to have an advantageous combination of lower investment costs and higher efficiency. In this paper an atmospheric indirectly fired gasifier is selected. This is a fast fluidized bed gasifier fed by air [8]. Electricity production through a steam turbine is also considered in this study.

The installed investment costs for the separate units in the base 280,000 m^3 methanol plant are presented in Table 1. Scale effects strongly influence the unit cost per plant capacity, which decrease with larger plants or equipments (such as boilers, turbines etc.). For example, a methanol plant of 100 MW can be expected to be cheaper per $GJ_{methanol}$ produced than a 10 MW plant, even though both plants are based on the same basic technology. This difference can be adjusted using scaling functions of the individual components of the plant as described in equation (3):

$$\mathrm{Cost}_a/\mathrm{Cost}_b = (\mathrm{Size}_a/\mathrm{Size}_b)^R \tag{3}$$

where R is the scaling factor, Cost_a and Cost_b are the costs of the components for two different biofuel plants with Size_a and Size_b. Using this information it is possible to calculate costs for different processing steps of methanol plants with different sizes. By adding investment costs from the separate units, the total investment cost for another size can be determined, and production cost for the respective methanol plant can be calculated. For biomass systems, R is usually between 0.6 and 0.8 [14]. The uncertainty range of such estimates is up to $\pm 30\%$ [8].

From the process plant costs (Table 1), the total capital requirement can be calculated as presented in Table 2. The total capital requirement is used for calculating the annual cost (AC) as given by equation (4):

$$\mathrm{AC} = \mathrm{TCR}\cdot\mathrm{IR}/\left(1 - 1/(1+\mathrm{IR})^{t_e}\right) \tag{4}$$

where TCR is the total capital requirement, IR is the interest rate and t_e, the economical lifetime. The annual operating and maintenance costs are calculated as the sum of the elements presented in Table 3.

Table 1 – Base scale factors for a 430 $MW_{biomass}$ methanol plant [7,8].

Gasification system	R	Base scale (M €)
Total pretreatment	0.79	31.4
Gasifier	0.65	25
Gas cleaning:		
Tar cracker	0.7	7.6
Cyclones	0.7	5.6
Heat exchanger	0.6	9.2
Baghouse filter	0.65	3.4
Condensing scrubber	0.7	5.6
Syngas processing:		
Compressor	0.85	13.9
Steam reformer	0.6	37.8
Methanol production:		
Make up compressor	0.7	14.3
Liquid phase methanol	0.72	3.6
Recycle compressor	0.7	0.3
Refining	0.7	15.7
Power generation:		
Steam turbine + steam system	0.7	11.4
Process plant cost (PPC)		184.8

Table 2 – Total capital requirement [15,16].

Capital required	Description
Total plant cost (TPC)	
Engineering fee	10% of PPC
Process contingency	2.345% of PPC
General plant facilities	10% PPC
Project contingency	15% of (PPC + general plant facilities)
Total plant investment (TPI)	
Adjustment for interest and inflation	0.34% PPC
Total capital requirement (TCR)	
Prepaid royalties	0.5% of PPC
Start-up costs	2.7% TPI
Spare parts	0.5% of TPC
Working capital	3% TPI
Land, 200 acres	200 acres at 6500 € Acre^{-1}

2.4. *Transport of methanol to the filling stations*

Depending on the quantity, infrastructure and distance, methanol can be transported by truck, train, or ship. Truck transportation is cost efficient for shorter distances, and train and ships for longer distances [7]. As methanol is transported to gas stations on distances around 100 km in Baden-Württemberg, only truck transportation is considered for the distribution of methanol. The costs of methanol transportation are calculated using figures from Börjesson and Gustavson [12], shown in equation (5).

$$C_{\mathrm{Truck}} = 138 + 3.05d \tag{5}$$

The transportation costs by truck (in € $TJ^{-1}_{methanol}$) are a function of actual transportation distance, d in km.

2.5. *Methanol distribution*

It is assumed that all gas stations are able to distribute methanol. As methanol is not widely used in the transportation sector, changes to gas stations would be required. Therefore, two scenarios may apply as outlined next. One can consider a station that has three underground storage tanks of three grades of gasoline, two pump islands, and four dispensers capable of refuelling eight vehicles simultaneously. At an average fill-up of 51 l requiring 6 min, a station

Table 3 – Annual operating and maintenance costs [15,16].

Operating and maintenance	Description
Wood	30 € m^{-3}
Operator labor	3% of TPI
Supervision and clerical labor	30% of O&M labor
Maintenance costs	2.2% of TPC
Insurance and local taxes	2% of TPC
Operating royalties	1% of wood cost
Miscellaneous operating costs	10% of O&M labor

such as the one illustrated may service between 200 and 400 vehicles per day and have a throughput of 321,760 l–643,520 l per month [17]. Two scenarios can be analyzed: (i) the first is to add a methanol capacity to an existing station, and (ii) the second considers that methanol would displace a fraction of existing gasoline storage capacity.

In the first scenario, it is assumed that the capability of dispensing up to 125,000 l of methanol per month is added to an existing retail gasoline station, increasing the overall throughput of a station. This may be accomplished by adding a new underground 37,900 l methanol fuel tank, remote from the existing tank field. An above ground tank might be added where space and permission is granted [17].

In the second scenario, it is assumed that a portion of the gasoline storage capacity of a station is displaced by a 38,000 l methanol storage tank. Alternative ways would be to eliminate one product from the mix of petroleum products and convert that storage capacity to methanol. This could be done by cleaning or upgrading one of the existing petroleum tanks and installing new methanol compatible piping and dispenser. It also includes removing one of the existing petroleum tanks and replaces it with a methanol compatible tank to upgrade the balance of the system.

The costs for handling a gas station of methanol with a capacity of 125,000 l per month are between 0.20 and 0.24 € $GJ^{-1}_{Methanol}$ regarding the chosen scenario. The later value is considered in the model.

2.6. Other technical and site specific data

First, the relation between the costs and the methanol plant size is studied. The different parameters and their values are presented in Table 4. In addition, a sensitivity analysis was carried out elucidating the impact of another five parameters on the methanol production costs. The calculations were performed for 2 methanol plants situated at 48.15°N, 9.5°E, and 49°N, 9°E, where the first one (plant A) is situated closer to high biomass production areas and the second one (plant B) is located closer to a high demand areas. The wood cost has been studied with an upper and lower value equal to twice and half the reference cost respectively. The upper value would represent an increase of the wood cost due to a shortage in wood. The land allocation to energy wood is a parameter difficult to estimate; therefore we assume a range between 2.5 and 0.5 times of the reference value. Regarding the plant efficiency, as the technology is not fully commercialized, a reference value of 40% was chosen. About 57% was the value suggested by Hamelinck and Faaij [8], and an extreme lower value of 25% was assumed in case of technology deficiency. Finally concerning the plant operating hours, Hamelinck and Faaij [8] suggested 8000 h; Wahlund [18] reported operating hours below 6500 h per year for biomass-based heat and power plants. A reference value of 7200 h per year was then chosen where two months would be left for maintenance and eventual repairs. Those parameters are presented in Table 5 together with their extreme values (−1 and +1 levels). The sensitivity of these parameters is analyzed by a $2^{5-1}{}_V$ factorial design, where the influences on the costs of five parameters are studied, as well as their interactions with each other. This study is carried out with 16 runs with different combination between the parameters. The six columns on the left side of Table 6 present the combinations studied.

Table 4 – Reference parameters.

Description	Unit	Value
Wood cost [9]	€ m^{-3}	30
Land allocation[a]	ha	1852
Road to direct distance ratio		1.6
Plant efficiency [8]	%	40
Plant operating hours [8]	h	7200
Technical lifetime [8]	years	25

a The land allocation represents the area reserved for energy production for 1% of the total possible methanol consumption in Baden-Württemberg.

3. Results

3.1. Cost of methanol as a function of plant size

The total cost of methanol (from harvesting of biomass to methanol distribution to the consumers) with costs in € $GJ^{-1}_{Methanol}$ is presented in Fig. 1. The figure shows the cost components of biomass production and transportation, methanol production, transportation and distribution. The transportation costs increase with the size of the methanol plant while methanol production costs exponentially decrease with the size. The economy of scale offsets potential additional costs from biomass and methanol transportation assuming a scale independent region with uniform roadside and biomass market price.

3.2. Sensitivity analysis

In order to study the sensitivity and interactions of the parameters, a $2^{5-1}{}_V$ factorial design is analyzed. For each run, the different costs of the chain of methanol production are determined as previously outlined.

The normal probability plot of the effect is presented in Fig. 2 and results are listed in Table 6.

The larger effects that appear can be sorted into 3 groups (Fig. 2):

- the plant efficiency (*D*) which has the strongest influence,
- the wood cost (*A*) which is the second most influencing parameter,

Table 5 – Variables studied with attached extreme values.

Description	Unit	−1	Ref.	1
Wood cost [9]	€ m^{-3}	15	30	60
Land allocation	ha	4628	1852	926
Plant position	°E	9.5	–	9
	°N	48.15		49
Plant efficiency	%	57	40	25
Plant operating hours	h	8000	7200	6500

Table 6 – Results from the factorial design.

Run number	Wood cost, € m^{-3}	Land allocation, ha	Plant position	Efficiency	Plant operation hours, h	Transport cost, € $GJ^{-1}_{methanol}$	Production cost, € $GJ^{-1}_{methanol}$	Total, € $GJ^{-1}_{methanol}$
1	15	4628	A[a]	0.57	8000	1.76	9.76	15.03
2	15	926	B[b]	0.57	8000	2.43	9.76	15.7
3	15	4628	B	0.57	6500	1.74	12	17.24
4	15	926	A	0.57	6500	2.46	12	17.97
5	60	4628	B	0.57	8000	1.8	9.85	24.96
6	60	926	A	0.57	8000	2.62	9.85	25.78
7	60	4628	A	0.57	6500	1.71	12.1	27.12
8	60	926	B	0.57	6500	2.31	12.1	27.72
9	15	4628	B	0.25	8000	3.78	22.24	33.72
10	15	926	A	0.25	8000	5.51	22.24	35.44
11	15	4628	A	0.25	6500	3.45	27.36	38.5
12	15	926	B	0.25	6500	4.96	27.36	40.01
13	60	4628	A	0.25	8000	3.56	22.47	56.06
14	60	926	B	0.25	8000	5.24	22.47	57.74
15	60	4628	B	0.25	6500	3.65	27.58	61.27
16	60	926	A	0.25	6500	5.16	27.58	62.78

a Position A: 9.5°E, 48.15°N.
b Position B: 9°E, 49°N.

- and the interaction between the plant efficiency and the wood cost (AD), the plant operating hours (*E*), the interaction between the plant efficiency and the operating hours (DE), and the Land allocation (*B*).

3.3. *A geographical analysis*

In the geographical analysis, two methanol plants of 200 $MW_{Biomass}$ each were studied with the model detailed earlier based on minimization of the costs of the supply chain. The methanol plant A is situated in an area with high biomass production and the methanol plant B is situated in an area with a high methanol demand, in the proximity of Stuttgart. For the road to direct distance factor, the values of 1.5 and 1.45 for the methanol plants A and B were used respectively. Other parameters are presented in Table 4.

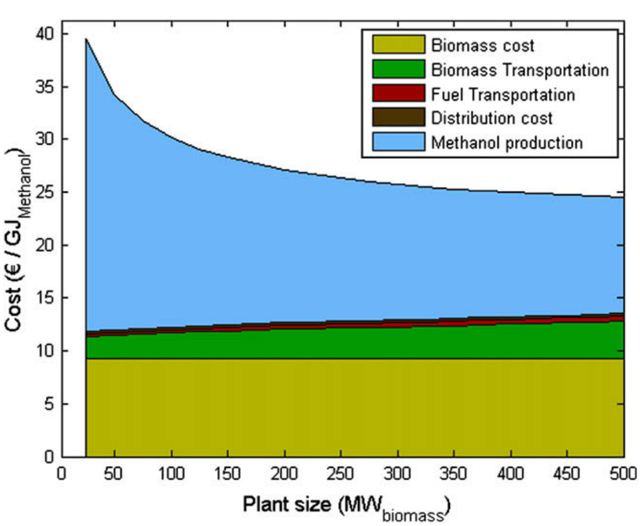

Fig. 1 – Cost of methanol (in € GJ^{-1}) by the size of the biofuel plant (in $MW_{biomass}$).

Such methanol plants are able to supply 147 gas stations per year using biomass that is produced within a circle of 50 km of radius (Fig. 3). Table 7 lists the production characteristics and costs for the 200 $MW_{Biomass}$ plants.

4. Discussion

4.1. *Energy demand*

Fig. 3 illustrates the geography of biomass production supplying each methanol plant. The largest distance of biomass supply for plant A is 55 km and for plant B, 70 km.

There are 1032 gas stations located in Baden-Württemberg. If all stations deliver methanol to consumers, then about 6.78 T $Wh_{Methanol}$ year^{-1} need to be supplied. The simulated average annual production of short-rotational poplar coppice in Baden-Württemberg is 13.48 Mt year^{-1}, which corresponds to 67.04 T Wh year^{-1}. About 234,200 hectares of short-rotational poplar coppice would be needed to make Baden-Württemberg self-sufficient in methanol production.

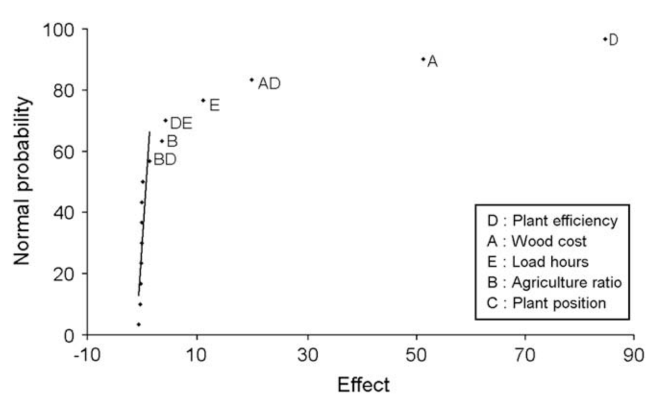

Fig. 2 – Normal probability plot of effects. Parameters with large effect have more influence on the total cost.

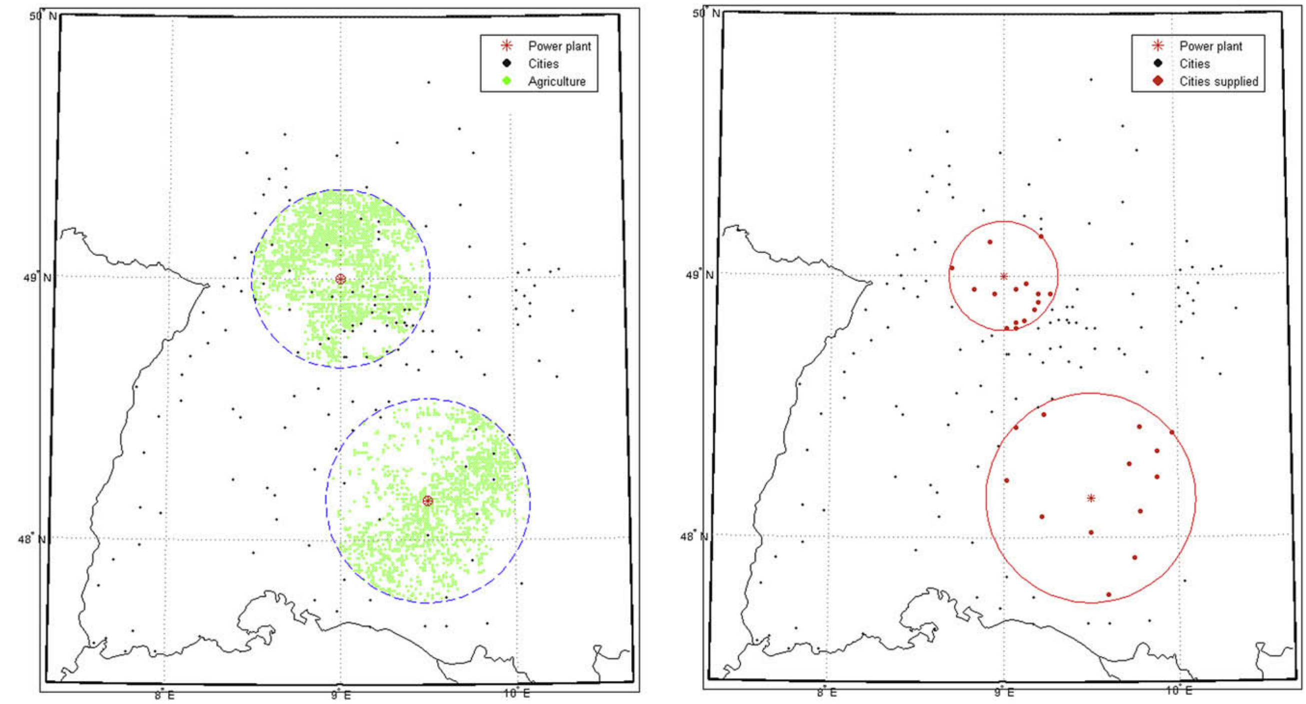

Fig. 3 – Geography of two 200 $MW_{biomass}$ methanol plants in the county of Baden-Württemberg. Left: the circles represent the woody biomass used by each plant (center of circles). Right: the circles represent the cities that are delivered in methanol by each plant (center of circles). The remaining black cities are not delivered in methanol.

The effect of scale economies in methanol production is illustrated in Fig. 1. For a plant of 200 $MW_{Biomass}$, the total cost of the methanol production chain consists of biomass costs (36%), biomass transport costs (17%), methanol transport costs (3%), methanol distribution costs (1%), and methanol production costs (43%). The costs for the average set-up are estimated to be below 30 € $GJ^{-1}_{Methanol}$, which corresponds to 0.50 € $l^{-1}_{Methanol}$, or 1.0 € $l^{-1}_{Gasoline\ equivalent}$. Sensitivity analysis reveals a wide range of plausible cost estimates, some 50% higher and lower this central estimate.

Table 7 – Production characteristics and costs for the 200 $MW_{biomass}$ methanol plants.

Results	Units	Plant A	Plant B
Longitude	°East	9.5	9
Latitude	°North	48.15	49
Wood	$t\,h^{-1}$	40	40
Methanol sold	$l\,day^{-1}$	438,000	438,000
Area	ha	28,140	351,400
Gas stations		99	106
Population		409,149	538,855
Biomass transports			
Mean	€ $GJ^{-1}_{methanol}$	2.21	2.13
Max	€ $GJ^{-1}_{methanol}$	2.72	2.52
Biomass radius	km	65.1	54.92
Fuel transports			
Mean	€ $GJ^{-1}_{methanol}$	0.29	0.22
Max	€ $GJ^{-1}_{methanol}$	0.34	0.24
Delivering radius	km	66.79	35
Production costs	€ $GJ^{-1}_{methanol}$	15.03	15.03
Annual costs	€ $GJ^{-1}_{methanol}$	8.91	8.91
Operating costs	€ $GJ^{-1}_{methanol}$	6.11	6.11
Gas station costs	€ $GJ^{-1}_{methanol}$	0.24	0.24
Fuel cost			
Min	€ $GJ^{-1}_{methanol}$	26.99	26.33
Max	€ $GJ^{-1}_{methanol}$	27.07	26.8

4.2. *Model parameter sensitivity*

The most important factor influencing costs in the methanol production chain is the plant efficiency (factor *D*). A difference from 0.25 to 0.57 in the methanol plant efficiency would double the production costs as well as the total methanol cost (comparisons between the runs 4 and 12). However, the technology for methanol production through gasification is not yet proven or commercially available, process efficiencies over 50% might be expected as analyzed from Hamelinck and Faaij [8].

The biomass cost is the second parameter that substantially influences the final methanol cost. An increase in the raw material by a factor 4 would raise the final methanol cost by 63% (comparisons between the runs 10 and 14).

The plant operating hours and the land availability are the two last parameters that influence the final methanol cost. A difference of the plant operating hours from 6500 to 8000 h may lead to an increase in the production cost by 23% and in the final methanol cost by 14.8% (comparisons between the runs 9 and 11). If there is, for instance 20% less land available within each grid cell for biomass production in this region then it would increase transport costs by 41.8%, and the final methanol cost would rise by 4.2% (comparisons between the runs 3 and 4).

The location of the methanol plant can influence the methanol cost. Biomass transport costs are higher for the plant A (2.21 € $GJ^{-1}_{Methanol}$) than for the plant B (2.13 € $GJ^{-1}_{Methanol}$), as well as the methanol transport (0.34 € $GJ^{-1}_{Methanol}$ for the plant A, and 0.24 € $GJ^{-1}_{Methanol}$ for the plant B, see Table 7). The plant B is indeed situated closer to the demand, and the transport infrastructure is more developed than in the area of the plant A, which was interpreted in the model with two different road to direct distance ratios. Moreover, the simulated yields of poplar coppice vary between 750 ODT $year^{-1}$ (oven dry tones per year) and 1150 ODT $year^{-1}$ in Baden-Württemberg, and the geographical repartition of poplar coppice is very dense all over the county, which can explain the small changes in the transport cost.

A 200 $MW_{Biomass}$ methanol plant needs about 140 ODT h^{-1} of biomass. Considering a 12 working hour day for the biomass transport by truck, one would see a truck (alternatively empty or fully loaded) between the biomass production site and the methanol plant every 4 min. Such heavy traffic would face poor public acceptance and thus emphasizes the importance of locating the methanol plant optimally given further geographic and social constraints.

5. Conclusion and future work

Methanol production through gasification carries the potential of considerable environmental benefits while producing transport fuels potentially in a cost competitive manner. To achieve the latter, an efficient production and processing technology as well as optimal plant location and logistics are required. Indeed, the process efficiency and the plant operating hours of the methanol plant, together with the biomass cost, appeared to have the biggest impact on the final methanol cost. Methanol cost can double between process efficiencies of 0.25 and 0.57. The location of the methanol plant may influence the transport cost by 60%. Baden-Württemberg is a particular example where biomass and gas stations are evenly spread all over the region; in a country where wood supply and fuel demand are at two different geographic positions, methanol plant location would have a decisive impact on the methanol price.

REFERENCES

[1] Ogden JM, Steinbugler MM, Kreutz TG. A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles. Journal of Power Sources 1999;79:142–68.

[2] RIRDC. Wood for alcohol fuels, status of technology and cost benefit analysis of farm forestry for bioenergy. RIRDC Publication No 02/141; 2002.

[3] Pacific Northwest Pollution Prevention Resource Center (PPRC). Alternative fuels for fleet vehicles. Available from: <www.pprc.org/pubs/altfuels.cfm>; 1999.

[4] Ahlvik P, Brandberg AR. Well-to-wheel efficiency for alternative fuels from natural gas or biomass. p. 85. Borlänge, Sweden: Swedish National Road Administration; 2001.

[5] Wahlund B, Yan J, Westermark M. Increasing biomass utilisation in energy systems: a comparative study of CO_2 reduction and cost for different bioenergy processing options. Biomass and Bioenergy 2004;26:531–44.

[6] Dornburg V, Faaij APC. Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies. Biomass and Bioenergy 2001;21:91–108.

[7] Sørensen ÅL. Economies of scale in biomass gasification systems. Laxenburg: International Institute for Applied Systems Analysis (IIASA); 2005.

[8] Hamelinck CN, Faaij APC. Future prospects for production of methanol and hydrogen from biomass. Utrecht: Utrecht University, Copernicus Institute, Science Technology and Society; 2001.

[9] Schönhart M. Profitability of short rotation forestry in Austria. Laxenburg: International Institute for Applied Systems Analysis (IIASA); 2006.

[10] Schmid E, Balkovic J, Moltchanova E, Skalsky R, Poltarska K, Müller B, et al. Bio-physical process modelling for EU25 – concept, data, methods and results. Final research report for the EU-FP6 research project INSEA. p. 76. Laxenburg: International Institute of Applied System Analysis (IIASA); 2006.

[11] Williams JR. The EPIC model. In: Computer models of watershed hydrology. Highland Ranch, Colorado: Water Resources Publication; 1995. p. 909–1000.

[12] Börjesson P, Gustavson L. Regional production and utilization of biomass in Sweden. Energy 1996;21:747–64.

[13] Volvo Truck Corporation. Emissions from volvo's trucks. Available from: <www.volvotrucks.com>; 2006.

[14] Tijmensen M, Hooidonk GV. Long term perspectives for production of fuels from biomass; integrated assessment and RD & D priorities – final results. Utrecht: Utrecht University, Copernicus Institute, Science Technology and Society; 2000.

[15] Craig KR, Mann MK. Cost and performance analysis of biomass-based integrated gasification combined-cycle (BIGCC) power systems. NREL/TP-43021657; 1996.

[16] Parsons EL, Shelton WW, Lyons JL. Advanced fossil power systems comparison study. NETL USDOE final report; 2002.

[17] Amf-Ea. Engineering, methanol refueling station costs. Prepared for American methanol foundation. Silver Spring: Science and Technology, Inc.; 1999.

[18] Wahlund B. Rational bioenergy utilisation in energy systems and impacts on CO_2 emissions. Stockholm: Chemical and Engineering and Technology; 2003.

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Short Communication

Attitudes towards forest, biomass and certification – A case study approach to integrate public opinion in Japan

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ABSTRACT

The purpose of this study was to contribute to filling the knowledge gap in public opinion and knowledge about forest and its certification in Japan, as well as to identify key elements and the possible role of public opinion within integrated bottom-up policies, bridging the sectors of forest, environment and energy. For the study 1930 questionnaires were disseminated in a small town in early 2007. Results from the statistical analysis indicated that forest was perceived as an ecosystem with a protective function against e.g. soil erosion or flooding, rather than a place that might serve for wood production and providing jobs. Forest certification and bioenergy from forest were identified as key elements for future integrated bottom-up policies that need to concentrate on facilitating the linkage between forestry and renewable energy as well as on promoting environmentally sound management and forest certification.

1. Introduction

According to the International Energy Agency (IEA, 2008), biomass for bioenergy will be essential in reducing the carbon intensity of energy production and decoupling energy use from CO_2 emissions. Japan's current contribution of biomass-based bioenergy (incl. waste) to its total primary energy supply is about 1% (METI, 2006) and hence still far away from playing an important role. This low share of renewable energy deriving from biomass is diametrically opposed to what might be expected from the fact that more than 60% of the land cover in Japan is forest – a main resource for energetic biomass with large domestic potential (Kinoshita et al., 2009). Japanese forests feature an annual increment of about 100 million m^3 but only 15% is harvested mainly due to a combination of low wood prices, high labor costs, and lack of appropriate forest infrastructure. Especially a modern and dense forest infrastructure (e.g. the forest road system or adequate harvesting systems for steep terrain) is seen as essential for cost-effective and competitive wood production and market access. However, most of Japanese forestry – the small-scale forestry in particular – has not seen any investment throughout the last decades. Consequently, about 81% of the total wood supply originates from overseas, which is flooding the market and threatening the remaining industry. Wood export practically does not exist (MAFF, 2008). Another observable fact of the Japanese forest sector industry is a certain resistance against any forest certification and wood product labeling on a large scale, which could help with assuring and promoting a responsible and sustainable forest management (SFM) and serve as a product marketing tool. Forest certification in general is seen to be successful in raising awareness and disseminating knowledge on a holistic SFM concept, embracing economic, environmental and social issues, worldwide (Rametsteiner and Simula, 2003). But while many European countries such as Austria or Finland - with similar or higher forest cover than Japan (both countries are also well known for their strong forest-based bioenergy sector) - have certified up to 100% of their forest area, the Japanese certification rate is only about 1%, which is even lower than that of many tropical developing countries (Kraxner et al., 2007).

As a first countermeasure, recent national policies started aiming at an increased use of domestic wood for bioenergy (Kuzuhara, 2005). Following the idea by the Japanese Ministry of Environment for achieving a "Low Carbon Society" (NIES, 2008), existing bioenergy plants could be fired with environmentally sound grown, domestic forest residues rather than with low-priced wood chips of frequently non-sustainable origin, shipped from Australia, Canada, or tropical countries such as Indonesia (FAO, 2008). However, in order to successfully tackle the pressing problem of a small share in bioenergy and little use of the domestic forest resource, further information from empirical social sciences and related evaluation research need to be provided to, and integrated by, policy makers. Despite its relevance for forest-, environmental-, energy- and social politics, relatively little is known about the

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attitudes of the Japanese public towards the topics of forests and biomass, their sustainable management and certification, or the use of this renewable resource for energy. Only a few surveys including forest related questions have been carried out by governmental or research institutions (e.g. MAFF, 2007; Owari and Sawanobori, 2007).

Thus, the main objectives of this study were (i) to contribute to filling the knowledge gap in public attitudes and knowledge about forest, forestry, biomass and its certification, and (ii) to identify effective ways of how the obtained knowledge of public opinion could contribute to integrated bottom-up policies for an enhanced use of domestic forest resources, complementary to the top-down policies established recently in the area of bioenergy.

2. Methods

A questionnaire-based drop-off survey was conducted in early 2007 among all households of Yusuhara Town which had been identified as an optimal case study location and selected because of its forest owners' cooperative. The town, located in the Kochi Prefecture on Shikoku Island, is a representative Japanese rural mountain community, offering a wide range of biomass resources for energy use e.g. wooden resources from thinning and the sawmill industry. Yusuhara Town has an area of 236.5 km^2, 91% forest coverage (of which 80% is privately owned) and a population of 4625 people in 1930 households (as of 2007). Forestry is the main economic activity in the town, with an annual turn over of about 600 million Yen in 2004 (Ota, 2006). Many of the local households are also members of the Yusuhara Forest Owners' Cooperative (YFOC). The cooperative achieved the first owner group forest management certification of international standard in Japan (2000) by the Forest Stewardship Council (FSC) for its 11,371 ha forest. This ambitious project had been mainly driven by an expected price premium and improved market access for its products.

The questionnaire was divided into 5 sections (general info, forest, forestry, biomass, and environment) in each of which 4–8 questions were asked with main focus on forest certification and biomass for bioenergy. The answers were made on a 5/6 point scale, or in dichotomous-choice form and analyzed by using SPSS. The valid response rate was 40%. In order to facilitate an evaluation and improve the interpretation of the perceptions and attitudes derived from the statistical analysis, results were compared with other national surveys where appropriate.

3. Results and discussion

As for the general questionnaire results, 80% of the respondents declared to be forest owners. The majority (70%) of the respondents were older than 50 years old. Since Yusuhara Town is a typical Japanese rural town suffering from weak or stagnating development, the findings indicated an aging problem. Along with over-aging, the town is facing certain depopulation, having lost more than half of its citizens since the late fifties. 15% of the local people stated to be retired or unemployed. Reflecting the importance of forest industry in the area, this industry sector was thought to be especially important for Japan by the majority (86%) of the respondents. This clear statement of highly valuing the local key industry turned into a somewhat different view when asking about various forest functions. Here the perception among the public shifted from a more product-oriented view when talking about the importance of the forest industry, towards the preference of ecosystem services as the most important forest functions. To be more precise, 82% of the respondents stated that the protective functions such as protection from disasters (e.g. soil erosion, flooding, avalanches), the provision of clean water, as well as the carbon storage function were most essential. On the other hand, the classical forest function of wood production was judged less important by only 55% of the respondents. Moreover, also the opinion that forest was a source for employment and job opportunities was rather weak (47%). This is a peculiar finding in a region which is dependent to a large extent on the forest as a resource for the production of biomass and timber, as well as work and income - directly or indirectly - to many local households. The fact that such kind of finding was not only a local exception, is supported by the results of a survey undertaken by the Japanese Cabinet Office on a national basis (MAFF, 2007). Respondents to this governmental questionnaire explained that they primarily expected high carbon sequestration capacity and disaster protection from the forest rather than wood production or the possibility for mushroom picking or other non-wood forest products.

Such impressions and expectations can be perceived as symptomatic for a threatened industry sector that is facing difficult times and has been abandoned for a long period already. It may also mean that people do not see their personal or regional future made up from income from forest products. A certain paradigm shift from production towards protection and the increased environmental role for forests being e.g. a pool of biodiversity, is identified when analyzing the results regarding forest functions.

The answers obtained from the forest function questions of this study were also analyzed by different job groups. A cross-analysis illustrated a specific pattern similar to the trends derived from the total sample, though with subtle differences between job groups. Farmers and foresters showed quite similar attitudes towards forest functions, whereas company workers or unemployed (including retired) people indicated different thoughts (Fig. 1).

Fig. 1 clearly shows that the highest agreement among all job groups as to what constituted the most important role of forest was found for technical and natural functions such as forest as an important ecosystem (80%) and water provision (80–90%), as well as for protective functions such as disaster prevention. The lowest importance (30–40%) was attributed to forest's role as a place for recreation. The highest discrepancy was identified between job groups with regard to forest's role as a place for wood production and job provider. Whereas foresters and farmers considered these functions to be relatively important – even though other functions were estimated more important – company workers and unemployed (including retired) people rated these production functions not very much higher than recreation (40–60%). Generally, these job-specific findings might be interpreted such

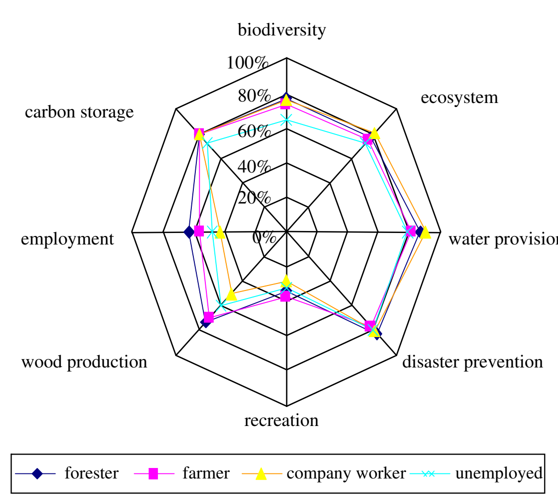

Fig. 1. Importance of forest functions by different job groups.

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that the closer the work to the topic of forest, the clearer becomes the positive attitude towards seeing forest as the traditional provider for timber, biomass and other wooden products. The further a job is placed from the topic of forest – e.g. company worker – the more the service-oriented function dominate the way of thinking. Additionally, these findings supported the results of the total sample analysis, indicating that even in the opinion of forest and agricultural workers, the classical forest functions seemed to be outdated, and that – under the present conditions of forest industry – nature protection and ecosystem services seemed to be considered as future functions.

As to agreement or disagreement on certain statements regarding the forest and its meaning to people, it turned out that there was an agreement among the job groups with respect to forest being good for the environment and climate, and that forest was a symbol of nature (Fig. 2).

However, Fig. 2 demonstrates that the situation was not this coherent with respect to the statements aiming at an increased use of forest, that – e.g. in the form of biomass – could be used energetically for bioenergy. Foresters clearly agreed (80%) with the idea of "using" the forest (in terms of harvesting and thinning for e.g. biomass) and also with the statement of "using the forest and protecting it" at the same time (80%), but did not agree so much with solely "protection" (60%). On the contrary, company workers strongly agree with the solely "protection" statement (70%) and agreed much less with the "use" (50%), as well as the combined "use and protect" notion (70%). Thus it can be noticed that there was a common understanding that the forest needed to be protected and that forest was a symbol for nature which was good for environment and climate. Nonetheless, the use of forest was perceived controversially within different job categories, showing that the acceptance to use forest decreased again with the distance of a job from the forest, e.g. only a minor share of company workers and unemployed (retired) people agreed to using the forest for harvesting actions.

So far we might say that such kind of attitudes and perceptions also reflect the raising environmental awareness in Japan during the past two decades (Barrett, 2005). This also incorporates a certain distance that has been growing between people and forest in Japan. Especially younger people believe – and this is obviously also proven by Japanese reality - that timber and wood products are simple commodities – similarly to steel or petroleum - that need to be imported while resources at home need to be protected, and for that, left untouched.

Finally, the recognition of the terms renewable energy, forest certification, and sustainable forest management (SFM) – key factors for public opinion integration into relevant bottom-up policies - were tested. Results indicated that more than 60% of the respondents were aware of forest certification, but less than 50% stated to have heard about SFM. The term renewable energy was recognized by slightly more than 50% of the respondents. The relatively high recognition of forest certification can be explained by the fact that the YFOC had been first in Japan to certify their forest, which attracted a great deal of media covering. On the other hand, SFM did not seem to be recognized as directly related to forest certification which confirmed that forest certification had been communicated more as an economic market tool for achieving a price premium or better market access, rather than an assurance for ecologically responsible forest management which would have been an asset in order to improve the outreach – considering that people are increasingly concerned about "green" issues.

In order to learn more details about the effects of certification on the public attitude, forest owner's opinion regarding harvesting – which again might ideally be used for bioenergy production – before and after a short and neutral explanation on forest certification was tested (Fig. 3).

The results from the t-test-analysis, as shown in Fig. 3, revealed that before receiving information on certification, slightly more than one-third of forest owners wanted to increase harvest in domestic forests rather than stop or stay with the same harvesting intensity. After having read the brief information on certification the opinion almost turned upside-down. Nearly two-thirds wanted to increase forest use and intensify harvesting after learning of certification. These findings can be interpreted such that forest owners, who were used to thinking in long term profitability (forest management is a long-term issue considering rotation periods of 50–100 years), on the one hand perceived the information regarding certification as a "green light" to immediately increase – in a controlled and standardized manner - both their harvest in a sustainable way and also their benefit (in terms of price premium or improved market access). On the other hand, forest owners might consider certification as a long-term investment and insurance for: (1) economic security - such as profit in terms of certified timber sales or biomass for bioenergy; harvesting actions under improved acceptance or even support from the public; (2) ecological benefits - need to be provided as services such as carbon sequestration and are assured in the form of a certified responsible forest management; as well as (3) social services - in terms of continuous and sustainable forest management which consequently leads to a stable forest structure and ensures public protection from e.g. flooding and soil erosion, or the provision of clean water.

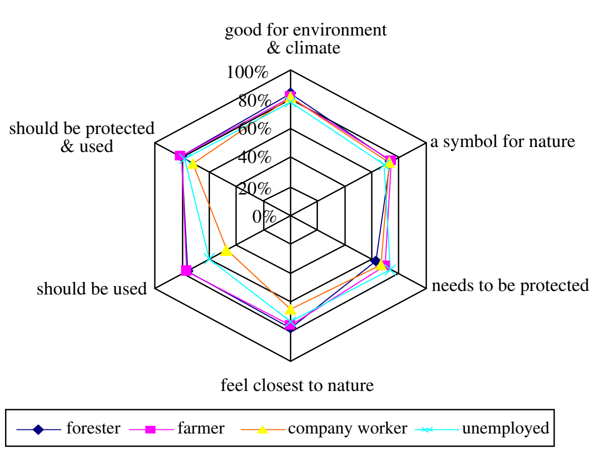

Fig. 2. Agreement to statements on the meaning and use of forest by different job groups.

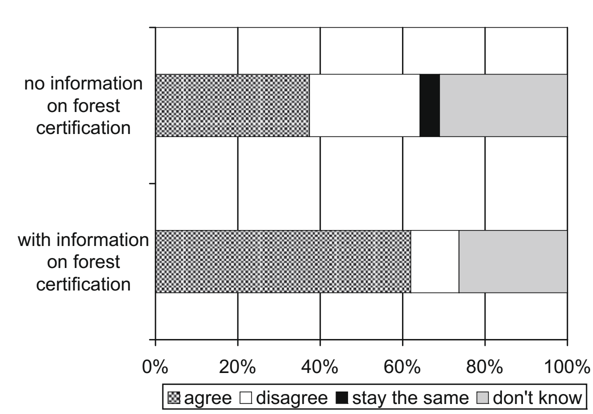

Fig. 3. Forest owners' attitudes towards increased harvesting and domestic forest use with and without prior information on forest certification (significant, $N = 589/567$).

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4. Conclusions

With the need of climate change mitigation, forest policy, environmental policy and energy policy have to converge in Japan. Complementary bottom-up policies that integrate public opinion are useful in bridging different sectors. This study provides insights into the public's opinion and knowledge about forest and biomass and identifies certification as one key element that could – together with forest-based bioenergy – provide multiple co-benefits. Bioenergy is the link between the forest, environment, and the energy sector which opens new markets to forest owners. Forest certification can help reactivating forest use by providing the needed economic long-term perspectives to the forest owners and promoting positive aspects of an environmentally sound forest use. The latter is particularly important in an increasingly environmentally sensitive society. Future bottom-up policies need to consider the public opinion and aim at tackling the problems of low forestry activities and climate change issues by concentrating on increasing people's knowledge and positive attitudes towards an environmentally sound use of domestic forests by promoting sustainable forest and forest certification as necessary drivers. For reaching a majority of people, further research on a national level is needed which contributes to stressing the ''green'' aspects of forest management.

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References

Barrett, F.D., 2005. Environmental discourses in a developmental state. In: Barrett, F.D. (Ed.), Ecological Modernization and Japan. Routledge, New York, pp. 12–24.

FAO, Food and Agriculture Organization of the United Nations, 2008. FAOSTAT, Forestry Trade Flows for Japan.

IEA, International Energy Agency, 2008. Energy Technology Perspectives 2008- Scenarios and Strategies to 2050, ISBN: 978-92-64-04142-4, 500.

Kinoshita, T., Inoue, K., Iwao, K., Kagemoto, H., Yamagata, Y., 2009. A spatial evaluation of forest biomass usage using GIS. Applied Energy 86 (1), 1–8.

Kraxner, F., Mater, C., Owari, T., 2007. Biomass for energy and plantations – new certification driver. In: UNECE/FAO Publications, Certified Forest Products Markets, 2006–2007", Geneva Timber and Forest, Study Paper 22, ECE/TIM/SP/22.

Kuzuhara, Y., 2005. Biomass nippon strategy – Why ''Biomass Nippon'' now? Biomass and Bioenergy 29, 331–335.

MAFF, Ministry of Agriculture, Forestry and Fisheries of Japan, Japanese Forestry Agency, 2007. Cabinet Office of Japan. Selected Survey Results on Forest and Life 2007 (in Japanese language).

MAFF, Ministry of Agriculture, Forestry and Fisheries of Japan, 2008. Preliminary Statistical Report on Agriculture, Forestry and Fisheries.

METI, Ministry of Economy, Trade and Industry of Japan, 2006. Energy in Japan 2006. Agency for Natural Resources and Energy.

NIES, National Institute for Environmental Studies, Kyoto University, Ritsumeikan University, and Mizuho Information and Research Institute (Eds.), 2008. 2050 Japan Low-Carbon Society Scenario Team, Japan Scenarios and Actions towards Low-Carbon Societies (LCSs).

Ota, I., 2006. Experiences of a forest owners' cooperative in using FSC forest certification as an environmental strategy. Small-scale forest economics. Management and Policy 5 (1), 111–126.

Owari, T., Sawanobori, Y., 2007. Analysis of the certified forest products market in Japan. Holz als Roh- und Werkstoff 65, 113–120.

Rametsteiner, E., Simula, M., 2003. Forest certification - an instrument to promote sustainable forest management? Journal of Environmental Management 67 (1), 87–98.

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SHORT COMMUNICATION

A new thinking for renewable energy model: Remote sensing-based renewable energy model

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SUMMARY

This paper mainly focuses on the two issues through remote sensing: assessment of the renewable energy potential and integration of the renewable energy model. Three methods for assessing the renewable energy potential with remote sensing (RS) are proposed. The methods can provide more precise evaluation of renewable energy potential, which is the first vital step to develop renewable energy model. The paper then first presents three integrations of the renewable energy model with RS and points out that with respect to the problems one of them is employed. The assessment methods based on RS and the integrations with RS are illustrated by a simple example with Europe solar energy data set. The results show that Germany is the optimal country to install photovoltaic with a capacity of 137 125 GW. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: renewable energy model; remote sensing; renewable energy potential; integrations with remote sensing

1. INTRODUCTION

The research for energy system has almost lasted for 70 years since the thirties of the 20th century when Krzhizhanovsky put forward the idea that energy economy should be approached comprehensively from production of energy sources to consumers [1]. The literatures involving the methodology of energy models are extensive [2–6]. Moreover, the bulk of models have been developed in, or among others [2–4,7]. In addition, some renewable energy models can be found in [8,9].

Although the methodology and the theory, however, have received most of the attention in energy/renewable energy models and in recent decades the renewable energy is advocated by

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extensive researches and many governments, two basic issues still need to be investigated: (1) the methods for precisely assessing the renewable energy potential and (2) the accuracy of the renewable energy models' results since these are the vital steps to model and invest the renewable energy.

The growing development of remote sensing (RS) shed light on the renewable energy models. The global satellites can quickly obtain RS data source, which shortens the time of gathering data. RS data has good spatial resolutions (e.g. the spatial resolution of QuickBird is 0.61 m), which contribute to the precise assessment of renewable energy potential closely. In fact, the evaluation of renewable energy potential is the first vital step to model the renewable energy. Clearly, the exactly large potential of renewable energy, together with the environmental advantages of renewable energy, will motivate the use of renewable energy and vice versa. In this paper, three methods with RS data are presented for assessing renewable energy potential. The methods take full advantages of the information of RS and can thus provide the more exact evaluation for renewable energy potential.

The increasing development of RS can improve not only the evaluation of renewable energy potential, but also the model result. Liu *et al.* [10] and Biberacher [11] have touched this issue. They used RS or Geography Information System (GIS) to visualize the model result and to some extent considered the integration of energy model with RS or GIS. However, they did not tackle this issue further. In this paper, an attempt is made to fill this gap. Three couplings are addressed and discussed in detail. These couplings make a good use of RS information and can thus provide better results, which approach much more the reality.

The remainder of the paper is as follows. The assessment methods based on RS for renewable energies potential will be discussed in the second section and the integrations of RS into renewable energy model in the third section. In the fourth section, the example illustrating the principle of assessment methods and integrations is designed. Finally, some conclusions are formulated.

2. ASSESSMENT METHODS FOR RENEWABLE ENERGY POTENTIAL

The assessment of renewable energy potential is a significant part of renewable energy model. It is the first important step to model the renewable energy. Traditional assessment methods are based on empirical model in which the experts' options are the major source, which in turn makes the assessment not very consistent. In addition, the costs for these methods are greatly high and it is hard to get the global contemporary renewable energy potential by using these methods.

The development of RS shed light on the assessment of the renewable energy potential since different resolution data for the same region are available and different precisions in modeling are thus possible. Moreover, the whole scale from regional to global is usable. Fischer and Schrattenholzer [12] and Günther *et al.* [13] employed RS to estimate the biomass potential. However, it is difficult to find mature methods to estimate any other renewable energy potentials such as solar and wind. The geographical potential and the technical potential, as well as the economical potential, provide a promised solution for assessing the renewable energy potential.

2.1. Geographical potential

The theoretical energy potential refers to the maximal possible renewable energy. In most situations, the theoretical energy potentials of given regions are directly inputted into renewable energy model as the limitation to the possible used renewable energy. The theoretical potential, however, is far from the factual renewable energy potential because lots of factors (e.g. the availability of area) will influence the renewable energy potential. Consequently, the geographical potential is presented in order to consider the geographical impaction. The renewable energy geographical potential considering the geographical impaction refers to the available and suitable production of renewable energy for given region(s). The geographical information, such as the availability of area, can be obtained from the RS data. Note that the renewable energy geographical potential based on RS has the spatial

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resolution since RS data has the spatial resolution. The following expression defines the geographical potential based on RS:

$$G_i = f(X_i, \mathrm{RS}_i) \tag{1}$$

where G stands for the geographical potential, X stands for the vector of parameters used to evaluate the theoretical potential, RS represents the vector of RS parameters, the subscript i represents the grid of RS data throughout the paper.

For the geographical potential of solar energy, the following expression is used:

$$G_i = 10^3 * I_i * h * A_i \tag{2}$$

where I is the time-averaged irradiance ($\mathrm{W\,m^{-2}}$), $h = 8760\,\mathrm{h\,y^{-1}}$. A is the available area ($\mathrm{km^2}$).

However, owing to the difference of the science and technology strength over regions, the geographical potential does not reflect completely the possible energy used. As a result, the technical potential is proposed.

2.2. Technical potential

The technical potential is the geographical potential by the losses of conversion of the primary energy to secondary energy sources. The technical potential of renewable energy considers not only the geographical impaction but also the technical influence. Hence it can provide more factual potential for renewable energy. For solar energy, the technical potential can be as follows:

$$E_i = G_i * \eta_{m(i)} * \mathrm{pr}_{(i)} \tag{3}$$

where η_m is the conversion efficiency, pr is the performance ratio of the system, and G is the geographical potential of solar energy defined above.

The parameter η_m has close relation with both the PV cells and the module temperature. A bulk of literatures discussing the parameter η_m can be found in, or among others [14,15]. The parameter pr is defined as the ratio between the actual performance of the system and the performance under standard test conditions.

The technical potential is better than the geographical potential due to the introduction of two additional parameters, which are the conversion efficiency and the performance ratio. However, both the geographical potential and the technical potential cannot be influenced by any other energy options. In general, except the single renewable energy model, the general renewable energy models always contain more than one kind of renewable energy resources. As a consequence, the assessment of energy potential has to consider the influence of alternative energy because of the competition among different alternative energy resources. The Economical potential is thus addressed.

2.3. Economical potential

The economical potential is the total amount of technical potential derived at cost levels that are competitive with alternative energy. This method considers the competition with alternative energy under the cost level and it thereby can motivate the modeling for renewable energy. The following expression is taken as the economical potential of the solar energy:

$$C_i = \frac{a_i * (M_i + B_i) + C_{\mathrm{OM}(i)} * (M_i + B_i) + L_i}{E_i} \tag{4}$$

Where a is the annuity factor ($\mathrm{y^{-1}}$), L is the annual land rental price ($\mathrm{US\$m^{-2}\,y^{-1}}$), M is the investment cost of the solar technology ($\mathrm{US\$m^{-2}}$), B is the cost of the balance of system ($\mathrm{US\$m^{-2}}$), $C_{\mathrm{O\&M}}$ is the annual operation and maintenance costs as percentage of the total investment costs ($\mathrm{US\$m^{-2}\,y^{-1}}$), and E is the annual technical potential of cell ($\mathrm{kWhm^{-2}\,y^{-1}}$). Hoogwijk [16] has an extensive discussion about C.

3. INTEGRATIONS OF RENEWABLE ENERGY MODEL WITH RS

Although many energy models are global level [2–4], it seems hard to apply them to the globe before RS is integrated with energy models. And although energy modelers have an insight that different phenomena occur under different spatial scales and the preferred spatial scale depends on the analysis undertaken, they do not consider cautiously the spatial resolution for the geo-referenced data even though they use downscale/ upscale methods to obtain different scale data.

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Actually, the scale effect receives much attention in RS and GIS. Many data structures reflecting scale effect such as the pyramid data structure and quad-tree structure have been applied to reality. Combining RS with renewable energy will make that insight and the downscale/upscale method more natural. Moreover, the combination of renewable energy model with RS can provide better model results, which will be discussed in following sections. With respect to the integrated approaches, three coupling ways should receive attention.

3.1. Loose coupling

Loose coupling is often used in computer science. In this paper, it means each module runs individually and is then bridged through exchanging results. Formally, the renewable energy model with loose coupling always has a feedback mechanism in order to obtain the final results. The advantages of this coupling are obvious: it has as much flexibility and simplicity as possible. However, the flexibility and simplicity cause some problems. For example the efficiency of whole renewable energy model is decreased because of the feedback mechanism.

Figure 1 illustrates the loose coupling workflow. In this framework, RS module mainly calibrates the results coming from renewable energy model and then feedback to the renewable energy model. After receiving the feedback, the renewable energy model will change the spatial resolution or adds/removes model data. Through finite iterations, the model result will be converged to a final model result. Sometimes reference energy systems (RES) need to be modified during the iteration.

In general, when the spatial resolution between RS data and energy–economy–environment data is the same, the feedback mechanism is normal, just like the computer science. When the spatial resolution between RS data and energy–economy–environment data, however, is different, the feedback mechanism is complex. The original resolution cannot be kept, and either the downscale/upscale method or the GIS multi-scale extraction method should be taken. The compromise must be reached when running the RS-based renewable model with loose coupling. For multi-scale extraction methods from identical data set, consult Wang [17] or others [18,19].

3.2. Tight coupling

According to the first law of geography, the similarity of locations of neighbors forms the similarity of interesting attributes of neighbors. The pioneers, Cliff and Ord [20], Anselin [21] and Haining [22], had discussed this issue comprehensively and argued that there existed the spatial autocorrelation among the neighbor objects. The spatial autocorrelation has been proved in such as environmental and regional science fields by using the spatial analysis. As a result, the spatial analysis, which is an important component of RS, can impose additional constraints on renew-

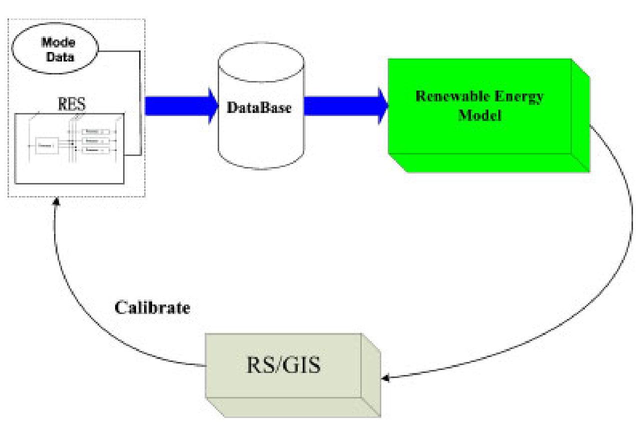

Figure 1. Loose coupling workflow.

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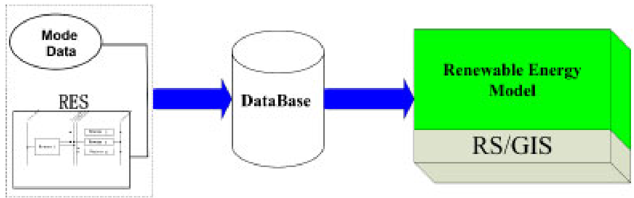

Figure 2. Tight coupling workflow.

able energy model. In this point, the renewable energy model and RS form an integration entity, which is called the tight coupling. The tight coupling workflow is depicted in Figure 2.

3.3. Mixed coupling

The loose coupling has much flexibility: adding/removing RS module is fairly easy, without changing the renewable energy model. The efficiency of this coupling, however, is substantially low due to the iteration feedback mechanism. In addition, it ignores the neighbor effect, which makes the results of renewable energy model invalid. On the contrast, the efficiency of the tight coupling is considerably high because of no iteration feedback mechanism. And the model result is closer to reality due to the consideration of neighbor influence. However, it loses the flexibility and makes the renewable energy model more complex. The mixed coupling takes good use of the merits of both couplings. But it is not the simple combination of these two couplings. In mixed coupling, both the RS constraints and the feedback mechanisms are employed. Before running the model, RS spatial operator, such as spatial overlay, are first used to reduce the impossible model result. Then, the tight coupling model runs and the result are calibrated by the feedback mechanism of the loose coupling. Because we use the RS spatial operator, the solution space becomes smaller and the whole system efficiency is thus improved, although the iteration feedback mechanism still exists.

4. CASE STUDIES

The methods developed above are illustrated by an example implemented by the BEWHERE model. The BEWHERE model is a bottom-up, multi-regions, and general equilibrium linear optimization model. Similar with other bottom-up models [2–4], it is devoted to the renewable energy technology rather than the renewable energy. The main target of the BEWHERE model is to determine the optimal locations to install new renewable energy plants by minimizing the system cost. The main constraints related with the paper consist of energy balance constraint, imports/exports symmetry constraint, energy capacity constraint and activity capacity constraint.

The renewable energy capacity of producing the electricity is fairly huge. According to BP statistic, the global technical potential of solar is about 23 times of the current global electricity consumption [23]. As a consequence, the solar energy is considered and the production flow of converting solar energy into the electricity through photovoltaic is taken. The studied area is confined to Europe. The country resolution is chosen because most of the decisions are made within the countries.

4.1. Data processing

The spatial resolution of the land-use data in 2004 obtained from IIASA [24] is 1×1 degree, which is not coincident with the country resolution. Using ArcGIS intersection tool, the land-use data with country resolution can then be obtained. By using the method introduced by Hoogwijk [16], the available area for each country can be obtained, illustrated in Table I. The PV module price data and the electricity trade price data[‡] in 2004, together with the electricity demand data in 2004, are obtained from IEA [25,26]. The solar

[‡]We simply think the trade price is the average sale price within country.

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Table I. Available area for Europe, 2004 (Unit: km^2).

Country	Available area
France	62 649
Norway	51 348
Sweden	40 553
Finland	37 212
Turkey	10 885
Germany	9470
United Kingdom	7909
Italy	7345
Poland	4410
Spain	4238
Denmark	2606
Switzerland	2604
Belgium	2442
Austria	1760
Greece	1714
Portugal	1626
Iceland	1217
Hungary	1192
Ireland	1119
Romania	943
Netherlands	939
Bulgaria	812
Czech Republic	749
Macedonia	577
Bosnia and Herzegovina	536
Albania	473
Slovenia	326
Cyprus	80
Luxembourg	53

irradiation data depicted by Figure 3 are obtained from NASA [27]. The data are the monthly average from July 1983 to June 1993. Because the solar irradiation is relatively stable within one or two decades, there is great confidence to regard that the 2004 solar irradiation is the same with the yearly average for July 1983–June 1993, which is the sum of the monthly average of 12 months. The solar geographical potential can then be figured out through expression (2).

The loose coupling is taken. The feedback mechanism is such that: running the BEWHERE model, the installed PV capacities for Europe are known. The needed areas for the PV capacity are then figured out. If the available area is greater than the needed area by region(s), the model result is the converged result. If not, the RES of the region(s) has to be divided into two RES. Then the new data for the new two RES will be gathered again and the preceding steps will occur. Note that during the feedback, the spatial resolution of the land-use data may be changed.

The model year is 2004 throughout the following analysis. Three scenarios are set up: scenario 1 is that no PV exists in Europe and imports and the exports merely happen within Europe countries under studying; scenario 2 is based on Table II. It means that some countries have past PV plants and others has none; scenario 3 is similar to scenario 1 with the difference that the technical potential randomly generated is taken instead of the geographical potential.

4.2. Results and discussions

According to Table I, we clearly know that the available area is smaller than the total area of country. Because the available area, however, takes into account of the impaction of the land-use type, it can do approach more the reality. As a consequence, the solar energy potential is more exact and meanwhile the results of the model are more accurate. The results of the model for the scenarios 1 and 3 are exactly identical: only Germany would have some PV installed (137 125 GW). This is because the available area of Germany is enough to install the PV plant with a capacity of 137 125 GW (see Table I) and the capacity is also enough to generate the needed electricity for Europe with the maximal profit. The results for the scenario 2 are presented in Table III. On the basis of Table III, it is evident that no new capacity of PV for other countries except Germany occurs and consequently Germany is the first choice to install PV and distributes the electricity to other Europe countries.

Summarily, on the basis of the results coming from three scenarios, it is evident that Germany is the optimal region to install PV. The interpretation is as follows: although the available area of Germany is not the biggest (see Table I) and so does the solar irradiation of Germany (see Figure 3), the results of the BEWHERE model are not only influenced by solar energy potential as well as available area but also influenced by such as PV module price factors. Because the BEWHERE model is

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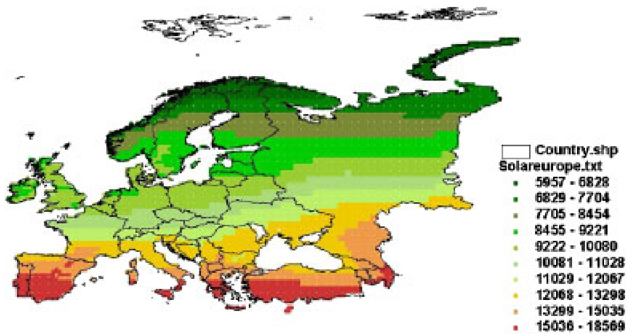

Figure 3. Yearly average Europe solar irradiation distribution from June 1983 to July 1993 (Unit: $\mathrm{Wh\,m^{-2}\,day^{-1}}$) [27].

Table II. PV capacity installed, Europe, 2003 (unit: MW) [25].

Country	Capacity
Germany	431.0
Netherlands	45.9
Spain	27.0
Italy	26.0
France	21.1
Switzerland	21.0
Austria	16.8
Norway	6.6
United Kingdom	5.9
Sweden	3.6
Finland	3.4
Portugal	2.1
Denmark	1.9

devoted to the renewable energy technology rather than the renewable energy, the technology price plays a more crucial role in minimizing the system cost. According to Figure 4, it is clear that the PV module price is the lowest. As a result, Germany is the optimal region to install PV and distributes the electricity produced from solar energy to other Europe countries.

Furthermore, to convince the preceding results, a well-known model called an acronym for The Integrated MARKAL EFOM1 System (TIMES) developed by ETSAP is taken. The TIMES model is an economical model generator for local, national or multi-regional energy systems and can provide a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon [3]. Under scenario 1, the results illustrated by Table IV indicate that

Table III. Total possible installed PV for Europe, scenario 2, result of the BEWHERE model (unit: GW).

Country	Capacity
Germany	137 124.8900
Netherlands	0.0459
Spain	0.0270
Italy	0.0260
France	0.0211
Switzerland	0.0210
Austria	0.0168
Norway	0.0066
United Kingdom	0.0059
Sweden	0.0036
Finland	0.0034
Portugal	0.0021
Denmark	0.0019
Albania	0
Belgium	0
Bosnia and Herzegovina	0
Bulgaria	0
Cyprus	0
Czech Republic	0
Greece	0
Hungary	0
Iceland	0
Ireland	0
Luxembourg	0
Macedonia	0
Poland	0
Romania	0
Slovenia	0
Turkey	0

Germany is still the first choice to install PV. The results, however, are considerably different with the one produced from the BEWHERE model because some countries, except Germany, also install PV in the TIMES model. The difference lies

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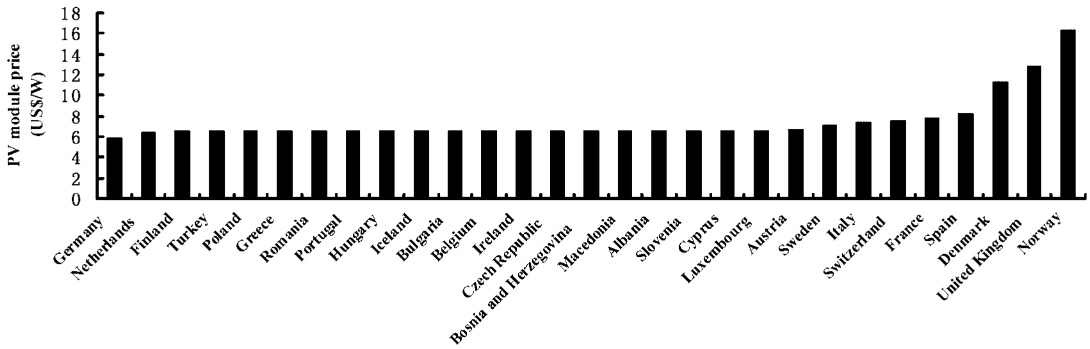

Figure 4. PV module price distribution, Europe [25].

Table IV. Total possible installed PV for Europe, scenario 1, result of the TIMES model (unit: GW).

Country	Capacity
Germany	35 562
France	15 334
Italy	10 896
Spain	8505
Sweden	4806
Turkey	4410
Netherlands	3802
Poland	3694
Finland	3065
Belgium	2972
Austria	2145
Switzerland	2071
Czech Republic	1984
Greece	1833
Portugal	1646
Romania	1429
Denmark	1215
Hungary	1173
Bulgaria	918
Ireland	803
Slovenia	464
Iceland	287
Bosnia and Herzegovina	264
Luxembourg	235
Macedonia	212
Cyprus	156
Albania	135

in the trade price, which is not considered among the studied countries in the TIMES model, whereas which does in the BEWHERE model. If the trade prices, which are the input parameters of the BEWHERE model, are less than the equilibrium prices of the TIMES model for countries, these countries prefer to import electricity from other countries.

5. CONCLUSIONS

Three assessment methods for renewable energy potential outlined in this paper provide a precise potential for renewable energy since they take advantage of RS information. The precise evaluation of renewable energy potential is significantly important to appeal to the use of renewable energy. Therefore, they are greatly useful for developing renewable energy model.

The integration of renewable energy model with RS is necessary when the further application of RS to renewable energy is obtained. Three couplings developed by the paper, which are the loose coupling, the tight coupling and the mixed coupling respectively, have their own advantages. With respect to the problems, one of the couplings was employed.

As is the case with the assessment methods and the integrations of renewable energy model with RS, the results of the model with Europe solar energy data set show that Germany is the optimal country to install photovoltaic with a capacity of 137 125 GW.

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REFERENCES

1. Belyaev LS, Kononov YD, Makarov AA. Methods and models for optimization of energy systems development: Soviet experience. In *A Review of Energy Models,* vol. 3, Beaujean JM, Charpentier JP (eds). International Institute for Applied Systems Analysis: Laxenburg, Austria, 1976; 1.
2. Messner S, Strubegger M. *User's Guide for MESSAGE III. WP-95-69*. International Institute for Applied Systems Analysis: Laxenburg, Austria, 1995.
3. Loulou R, Remne U, Kanudia A *et al*. *Documentation for the TIMES Model: Part 1*, 2005.
4. Fishbone LG, Abilock H. MARKAL, a linear programming model for energy system analysis: technical description of the BNL version. *International Journal of Energy Research* 1981; **5**:353–375.
5. Larsson T, Wene CO. Developing strategies for robust energy systems. I: methodology. *International Journal of Energy Research* 1993; **17**:503–513.
6. Larsson T. Developing strategies for robust energy system. Π: application to CO_2 risk management. *International Journal of Energy Research* 1993; **17**:505–535.
7. Nordhaus WD. An optimal transition path for controlling greenhouse gases. *Science* 1992; **258**:1315–1319.
8. IMAGEteam. *The IMAGE 2.2 Implementation of the SRES Scenarios*: *A Comprehensive Analysis of Emissions*, *Climate Change and Impacts in the 21st Century*. CDRom, Bilthoven, National Institute for public health and the Environment, 2001.
9. NREL. *HOMER-The Hybrid Optimization Model for Electric Renewables*. National Renewable Energy Laboratory: Colorado, 2000.
10. Liu J, Williams JR, Zehnder AJB *et al*. GEPIC—modelling wheat yield and crop water productivity with high resolution on a global scale. *Agricultural Systems* 2007; **94**(2):478–493.
11. Biberacher M. *Fusion in the Global Energy System—GIS and TIMES*. Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, 2007.
12. Fischer G, Schrattenholzer L. Global bioenergy potentials through 2050. *Biomass and Bioenergy* 2001; **20**(9):151–159.
13. Günther KP, Borg E, Wißkirchen K *et al*. Remote Sensing and modeling: a tool to provide the spatial information for biomass production potential. In *Use of Bioenergy in the Baltic Sea Region*, Barz M, Ahlhaus M (eds). *Conference Proceedings of 2nd International Baltic Bioenergy Conference IBBC*, Stralsund, Germany, 2006; 33–45.
14. Yamaguchi M. Present status and prospects of photovoltaic technologies in Japan. *Renewable and sustainable energy reviews* 2001; **51**:13–135.
15. Green MA, Emery K, King KDL *et al*. Solar cell efficiency tables (version 21). *Progress in Photovoltaics Research and Application* 2003; **11**:39–45.
16. Hoogwijk M. On the global and regional potential of renewable energy sources. *Ph.D. Thesis*, Utrecht University, Netherlands, ISBN 90–393–3640, 2004.
17. Wang SF. Research on key technologies about the spatial network analysis. *Master Thesis*, Institute of remote sensing applications, Chinese academy of sciences, Beijing, China, 2006.
18. NCGIA. NCGIS Research Initiative. Available from: http://www.ncgis.ucsb.edu. Accessed on November 10, 2007.
19. Egenhofer MJ. Heterogeneous geographic databases. Available from: http://www.ncaia.maine.edu. Accessed on November 10, 2007.
20. Cliff AD, Ord JK. *Spatial Processes: Models and Applications*. Pion: London, 1981.
21. Anselin L. *Spatial Econometrics: Methods and Models*. Kluwer Academic Publishers: Dordrecht, The Netherlands, 1988.
22. Haining R. *Spatial Data Analysis*: *Theory and Practice*. Cambridge University Press: UK, 2003.
23. BP. BP Statistical Review of World Energy 2002. Available from: http://www.bp.com. Accessed on December 10, 2007.
24. IIASA. Available from: http://www.iiasa.ac.at/. Accessed on December 27, 2007.
25. IEA. Available from: http://www.iea-pvps.org/. Accessed on February 28, 2008.
26. IEA. Available from: http://www.iea.org/. Accessed on February 28, 2008.
27. NASA. Available from: http://eosweb.larc.nasa.gov/sse/. Accessed on October 28, 2007.

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III.8. SBA HEALTH by GEO-BENE Consortium Partners

Prediction of daily AMI incidence based on the weather forecast. A case study of Finland.

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Abstract

The existence of a relationship between the daily weather, in particular, temperature, and health has been known for a long time. This environmental effect is especially large in the aetiology of cardiovascular and respiratory diseases. The most important single cardiovascular disease is coronary heart disease (CHD), including acute myocardial infarction (AMI). The morbidity and mortality of AMI in Finland is among the highest in the world, and varies widely across the country, exhibiting the well-known west-east gradient.

In this study we have examined daily incidence of the first AMI country-wide as well as in seven individual Finnish cities (Helsinki, Turku, Tampere, Jyväskylä, Kuopio, Oulu, and Rovaniemi) situated in the geographic range of (22-28ºE)*(60-67ºN) during the years: 1983, 1988 and 1993. The total number of cases was 36,798 and the corresponding total population at risk was 9,160,908.

Generalized linear regression modeling was applied to incidence of AMI, with the Fourier series terms and the weather covariates such as daily temperature mean and variation, humidity, wind speed etc. included.

We have found the log-linear time trend to be the single most significant factor in the evolution of the AMI incidence. Cross-validation analysis has shown that the addition of neither seasonality terms nor weather effects nor both improves the predictive power of the model with respect to the available Finnish data.

The short-term AMI mortality is influenced by the treatment quality and availability. It is therefore important to provide a model able to predict seasonal fluctuations in demand. The methodology for assessing the goodness of this prediction, presented here, is therefore a useful tool.

Introduction

The existence of a relationship between environmental factors, such as, e.g., daily weather conditions, and the human health has been known for a long time (Gerber *et al.*, 2006; Goerre *et al.*, 2007; Kunst *et al.*, 1993). Numerous studies have shown that weather extremes have an impact on mortality, notably due to cardiovascular and respiratory diseases (Basu & Samet, 2002; Braga *et al.*, 2002; Ebi *et al.*, 2004; Huynen *et al.*, 2001; Kunst *et al.*, 1993; Morabito *et al.*, 2005). Among these cardiovascular diseases, coronary heart disease and stroke are the major public health problems; CHD is the leading cause of death and disability (as measured in disability-adjusted life years, DALYs) in high income countries (Murray & Acharya, 1997; Murray, 2001). Projections for the year 2030 predict an even further increase in CHD prevalence, largely due to the expected population ageing, increase in the prevalence of type 2 diabetes, growing world affluence and climate change (Mathers & Loncar, 2006; Mokdad *et al.*, 2001; Murray, 2001). The acute myocardial infarction (AMI) is the major clinical event of CHD.

The reality of the process of climate change is now widely accepted in the scientific community. The Intergovernmental Panel on Climate Change (IPCC) has developed a number of climate change scenarios based on various assumptions regarding the demographic, social and economic development as well as technological change (IPCC, 2000). Based on observational and modeling studies across these scenarios, the weather is expected to consist of higher maximum temperatures and more hot days, fewer frost days over nearly all land areas and increased heat index (combination of temperature and humidity) in many areas (Frich *et al.*, 2002; Houghton *et al.*, 2001).

Since the climate change is a slow process, the opportunities for observing directly its effect on human health are limited. However, good quality empirical studies of the effects of weather or climate on health outcomes can provide the evidence base for developing risk-assessment models (Kovats *et al.*, 2005; Kovats & Kristie, 2006) The applicability of such studies, however, goes beyond purely epidemiological interest. After the heat waves during summer 2003 in Europe and of 1995 in the USA, a number of heat warning systems have been set up in Europe, Asia and the USA for predicting heat waves and being prepared for heat-related illnesses and excess deaths (Kalkstein, 2002; Kovats & Kristie, 2006; Pascal *et al.*, 2006).

Several weather factors have been suggested to increase the incidence and the mortality of AMI. Although the majority of the weather-related epidemiological studies so far have been concerned with the extreme heat conditions, especially after the European heat wave in August 2003 (see, e.g., (2004; Le Tertre *et al.*, 2006; Nogueira *et al.*, 2005; Simon *et al.*, 2005)), the extreme cold is also known to have an influence on health (Hassi *et al.*, 2005). Studies around the world have reported a seasonal pattern in AMI incidence with an excess rate in winter (Cheng, 2005; Gerber *et al.*, 2006; Kloner *et al.*, 1999). The exact reasons for this seasonality are still unclear (Cheng, 2005; Culic, 2006), but weather appears to play a significant role. A decrease of temperature was associated with increased daily event rates of AMI, with a stronger effect in older age groups (Danet *et al.*, 1999; Frost *et al.*, 1992; 1997). Braga *et al.* (2002) state that the effect of hot temperature on AMI mortality is twice as large as the effect of cold temperatures. Several studies have found an increase of coronary events a number of days after cold or hot temperatures. The effect of cold temperatures persisted for several days, whereas the effect of hot temperatures was observable only on short-term basis (Barnett *et al.*, 2005; Braga *et al.*, 2002). Other weather factors found to be related to the incidence and the mortality of AMI are decrease of air pressure and heavy wind activity (Danet *et al.*, 1999; Goerre *et al.*, 2007; Houck *et al.*, 2005). Most of the studies did not differentiate between first occurrence of AMI and recurrent cases. However, there is an indication that weather has stronger effects on recurrent cases of AMI (Danet *et al.*, 1999).

In Finland, being one of the northernmost countries in the world, the climate is primarily influenced by the geographical position. It is characterized by both a maritime and a continental climate. Due to the Gulf Stream and the influence of the continental climate, the mean temperature is several degrees higher than in other areas of the same latitude, with cold winters and comparatively hot summers. Weather types can change very quickly, as Finland lies in the zone where tropical and polar air masses meet. The seven Finnish city areas selected for this study: Helsinki, Turku, Jyväskylä, Tampere, Kuopio, Oulu and Rovaniemi, show rather similar climate characteristics, but differ from each other in certain aspects like wind strength and weekly variation of temperature. The average temperature follows roughly the geographical position of the cities, being coldest in the north and warmest in the south. The average winter temperatures differ more from city to city than the summer averages.

In this study we examine the predictive properties of four statistical models of increasing complexity on the example of Finnish AMI data, obtained for the years of 1983, 1988 and 1993. Our aim is to determine whether the accurate weather forecast is of use in short term AMI event rate prediction. The modeling was done within a generalized linear modeling (GLM) framework, and the accuracy of prediction was assessed through cross-validation.

Data

The data on Finnish AMI patients, 25-74 years of age, for the years 1983, 1988, and 1993 were obtained from nationwide registries: the Cause of Death Statistics and the Hospital Discharge Registry maintained by the National Research and Development Centre for Welfare and Health. The personal identification number assigned to all Finnish residents was used to perform a computerized record linkage of the Cause of Death Statistics data and the Hospital Discharge Register data for deaths and hospitalization due to AMI (International Classification of Diseases ICD-9 codes 410-414). Both fatal and non-fatal events were included in the study. The records were linked to trace back the possible earlier events of AMI, making the distinction between the first and the recurrent events possible. AMI cases were localized according to the municipality of the place of residence at the time of diagnosis.

The sex-age-municipality-specific population data were obtained from Statistics Finland.

The climate data was obtained from the European Centre for Medium-Range Weather Forecasts ERA-40 project (ECWMF, 2007; Uppala *et al.*, 2005). It consisted of interpolated measurements for air temperature, pressure and wind speed projected at 6h intervals. Comparison with locally available meteorological data exhibited high correlation.

For the purposes of this analysis the following seven larger Finnish municipalities were selected: Helsinki (60.2N, 24.9E), Kuopio (62.5N, 27.4E), Oulu (65.0N, 25.3E), Rovaniemi (66.3N, 25.4E), Tampere (61.3N, 23.5E), Turku (60.3N, 22.2E), and Jyvaskyla (62.1N, 25.4E) (Figure 1). Thus, the considered population-at-risk for the three study years was in total 1,319,964 men and 1,508,634 women.

Methods

The daily number of cases Y_t was assumed to follow a Poisson distribution:

$$Y_t \sim Poisson(\mu_t N_t),$$

where μ_t is the daily risk of suffering an acute myocardial infarction and N_t is the population-at-risk on that day. The Poisson parameter, in turn, is assumed to have a log-linear structure. Four models of increasing complexity were considered: a linear trend (LT) model, which assumes no seasonal effect, a Fourier series (FS) model, which, in addition to a linear trend, includes a combination of five seasonal effects (four annual subdivisions and a weekly period), a daily weather (DW) model, which includes daily weather covariates and a model which includes both, the Fourier series and the daily weather effects (FW). The mathematical representation of these four models is shown in equations (1-4) respectively.

$$\log(\mu_t) = \alpha + \beta X_t \tag{1}$$

$$\log(\mu_t) = \alpha + \beta X_t + \sum_{k=1}^{4} \left[a_k \sin(2\pi k X_t) + b_k \cos(2\pi k X_t) \right] + a_5 \sin(2\pi W_t) + b_5 \cos(2\pi W_t) \tag{2}$$

$$\log(\mu_t) = \alpha + \beta X_t + \xi Z_t \tag{3}$$

$$\log(\mu_t) = \alpha + \beta X_t + \sum_{k=1}^{4} \left[a_k \sin(2\pi k X_t) + b_k \cos(2\pi k X_t) \right] + a_5 \sin(2\pi W_t) + b_5 \cos(2\pi W_t) + \xi Z_t \tag{4}$$

where

X_t is the day (as counted from the 1 Jan 1983) divided by the average length of year, 365.25,

W_t is the day of the week (Sunday to Saturday), divided by the length of the week, 7,

Z_t is the matrix of weather-specific covariates, which in this study included the average temperature during the last week (both linear and quadratic term), the variation in the daily temperature during the last week, the pressure rate (both linear and quadratic term) and the wind speed.

All the models were fitted separately for the first and the recurrent AMI by sex*age group categories using R-software (R Development Core Team, 2007). The three age groups were 25-54, 55-64, and 65-74. To assess the predictive properties of the model a one-out and five-out cross-validation were performed and the resulting mean error (ME) and mean squared error (MSE) were evaluated. The five-out cross validation was chosen, because currently the weather forecasts are available for at most 5 days.

Results

The age-standardized estimated mean incidence rates by sex, study year and municipality as well as the corresponding 95% CI are shown in Table 1. There was some variation between the municipalities and a significant decrease in the incidence over the period 1983 – 1993.

During the study period the average daily temperature varied from -25°C in winter to +25°C in summer. The 90% inter-quartile range was narrow, from -13°C to 17.6°C. The average weekly standard deviation in temperature constituted 1.75°C, with the maximum reaching 3.13°C. The observed dependence of average daily incidence per 100 000 persons on the daily temperature is shown in Figure 2, together with a fitted loess curve.

The estimated coefficients for the most complete regression model (4) are shown in Table 2. The single consistently significant effect was due to the time trend, except for the recurrent attack rate for women aged 25-54, most likely, due to a very small number of cases. The estimated decrease of the first attack rate varied from 2.4% to 6.3% per year and from 5.5% to 11.2% for the recurrent attack rate. The seasonal and weather effects were found to be in general non-significant, although they were stronger for the recurrent cases and for older age groups.

Neither the one-out nor the five-out cross-validation showed any clear improvement in prediction after the addition of seasonal and weather variables, either separately or together (Table 3).

Discussion

The effect of hot temperature on the incidence of AMI has been found by studies in Italy, Netherlands, USA and other countries (Armstrong, 2003; Ballester *et al.*, 2003; Braga *et al.*, 2002; Kovats & Kristie, 2006; Messner, 2005). In Finland, the temperature ‘extremes’ are usually around 25°C compared to the mean annual temperature of 3-5 degrees. This temperature range might not be high enough to contribute to a clear effect on AMI incidence. In the case of other European cities the temperatures, and the extremes, are generally higher.

The effect of cold weather on the incidence of AMI was found for the cities that are situated in warmer climates than Finland. This effect could be marginal in Finland, because the population is acclimatized to cold temperatures. A European study comparing cold-related mortality from coronary heart disease (The Eurowinter Group, 1997) showed that cold-related mortality is associated with a high mean winter temperature of a region, i.e., warmer winters. The influence of cold temperature on coronary heart disease in general appears to be strongly modified by behavioural and social patterns such as clothing outdoors and heating indoors (Näyhä, 2005).

Despite a decrease in the AMI incidence in the last 30 years, Finland belongs to the high-incidence countries. Nevertheless the total population of 5.3 million people may not provide enough statistical power to detect a potential weather effect.

Some studies (Barnett *et al.*, 2005; Braga *et al.*, 2002; Kunst *et al.*, 1993) included time lags of temperature in their models. We included temperature lags for up to 17 days in our model at an earlier stage, but found no consistently significant effect. Additionally we have analysed the records for the first AMI cases in the comparatively hot year 1997, still finding no effect.

There have been reports of recurrent AMI being more affected by the weather compared to the first AMI (Danet *et al.*, 1999). In general, our analysis appears to agree: there was stronger evidence for the weather effect in these cases. However, the definition of the population at risk for the recurrent events is far from trivial. In principle, it should consist of those, who have had an AMI earlier. In practice such information is rarely, if ever, available and the denominator usually contains the total population at risk of AMI. In fact, the same applies to the analysis of the first AMI cases: the population at risk here should include only those who have not had an AMI before. However, in this latter case the bias is negligible, since the proportion of those who had an AMI is fairly small, whereas in the case of recurrent cases the bias is, for the same reasons, large.

In general, the population at risk is assumed to remain constant throughout the year although in reality it is more likely to experience seasonal variation, e.g., due to people leaving the city to spend their holidays in the countryside or abroad. Since it is not possible to evaluate or estimate the ‘real’ population at risk, these fluctuations are commonly assumed to be negligible.

In case of correlation between daily weather conditions and AMI incidence, hospital managers could use weather forecasts to plan capacity for the in-flow of cardiac patients. The more accurate the forecast, the less is the probability of (costly) over- or under capacity. Overcapacity is costly because of the opportunity costs of idle resources. Under capacity is costly because of an increase in the number of refused admissions. In case of AMI, the sooner the patient gets treatment, the better are his or her chances of not only survival but also of minimal residual damage (Norris, 2000).

An example of hospital capacity planning in case of the emergency in-patient flow of cardiac patients can be found in de Bruin *et al.* (2007). Applying queuing theory, they find a nonlinear relationship between the rate of daily arrivals and required hospital capacity. In their example, an 18 percent increase in daily arrivals doubles the percentage of refused admissions from 5% to 10%.

Hence, in the event of a totally unexpected increase in cardiac patients (for example, as a result of a heat wave), the rate of refused admissions would increase sharply, with negative impacts on health and possibly even resulting in increased mortality. If the increase can be expected (with some degree of certainty), a temporary expansion of capacity could reduce these negative health impacts.

From a socio-economic perspective, the optimal temporary expansion of capacity is a function of the costs of this expansion and the benefits of reduced health damage. In an uncertain world the optimal expansion of capacity would be a function of the costs and the *expected value* of the benefits. Hence, increasing the probability of the prediction of a heat wave may result in an increase of net health benefits, if the treatment capacity of the hospital can and will be temporarily increased in the event of, e.g., a heat wave.

Despite the possible weaknesses of this study it is most likely that the weather has very small effect on the risk of AMI in Finland. However, in other countries, more subjected to climatic extremes, the models formulated here, the generalized linear model which includes both Fourier terms and meteorological covariates may prove to be of use in predicting increased risk situations and conducting a more detailed cost-benefit analysis.

References

Armstrong B.G. (2003) Fixed factors that modify the effects of time-varying factors: applying the case-only approach. *Epidemiology*, **14**, 467-472.

Ballester F., Michelozzi P. & Iniguez C. (2003) Weather, climate, and public health. *J Epidemiol Community Health*, **57**, 759-760.

Barnett A.G., Dobson A.J., McElduff P., Salomaa V., Kuulasmaa K. & Sans S. (2005) Cold periods and coronary events: an analysis of populations worldwide. *J Epidemiol Community Health*, **59**, 551-557.

Basu R. & Samet J.M. (2002) An exposure assessment study of ambient heat exposure in an elderly population in Baltimore, Maryland. *Environ Health Perspect*, **110**, 1219-1224.

Braga A.L., Zanobetti A. & Schwartz J. (2002) The effect of weather on respiratory and cardiovascular deaths in 12 U.S. cities. *Environ Health Perspect*, **110**, 859-863.

Centers for Disease Control and Prevention (CDC) (2004) Impact of heat waves on mortality--Rome, Italy, June-August 2003. *MMWR Morb Mortal Wkly Rep*, **53**, 369-371.

Cheng T.O. (2005) Mechanism of seasonal variation in acute myocardial infarction. *Int J Cardiol*, **100**, 163-164; author reply 165.

Culic V. (2006) Seasonal distribution of acute myocardial infarction: a need for a broader perspective. *Int J Cardiol*, **109**, 265-266.

Danet S., Richard F., Montaye M., Beauchant S., Lemaire B., Graux C. *et al* (1999) Unhealthy effects of atmospheric temperature and pressure on the occurrence of myocardial infarction and coronary deaths. A 10-year survey: the Lille-World Health Organization MONICA project (Monitoring trends and determinants in cardiovascular disease). *Circulation*, **100**, E1-7.

de Bruin A.M., van Rossum A.C., Visser M.D. & Koole G.M. (2007) Modeling the emergency cardiac in-patient flow: An application of queueing theory. *Health Care Management Science*, **10**, 125-137.

Ebi K.L., Exuzides K.A., Lau E., Kelsh M. & Barnston A. (2004) Weather changes associated with hospitalizations for cardiovascular diseases and stroke in California, 1983-1998. *Int J Biometeorol*, **49**, 48-58.

ECMWF Data Server (2007) Available at http://data.ecmwf.int/data/ [20.06.2007].

Frich P., Alexander L.V., Della-Marta P., Gleason B., Haylock M., Klein Tank A.M.G. *et al* (2002) Observed coherent changes in climatic extremes during the second half of the twentiest century. *Clim Res*, **19**, 193-212.

Frost D.B., Auliciems A. & de Freitas C. (1992) Myocardial infarct death and temperature in Auckland, New Zealand. *Int J Biometeorol*, **36**, 14-17.

Gerber Y., Jacobsen S.J., Killian J.M., Weston S.A. & Roger V.L. (2006) Seasonality and daily weather conditions in relation to myocardial infarction and sudden cardiac death in Olmsted County, Minnesota, 1979 to 2002. *J Am Coll Cardiol*, **48**, 287-292.

Goerre S., Egli C., Gerber S., Defila C., Minder C., Richner H. *et al* (2007) Impact of weather and climate on the incidence of acute coronary syndromes. *Int J Cardiol*, **118**, 36-40.

Hassi J., Rytkonen M., Kotaniemi J. & Rintamaki H. (2005) Impacts of cold climate on human heat balance, performance and health in circumpolar areas. *Int J Circumpolar Health*, **64**, 459-467.

Houck P.D., Lethen J.E., Riggs M.W., Gantt D.S. & Dehmer G.J. (2005) Relation of atmospheric pressure changes and the occurrences of acute myocardial infarction and stroke. *Am J Cardiol*, **96**, 45-51.

Houghton J.T., Ding Y., Griggs D.J., Noguer M., van der Linden P.J., Dai X. *et al* (2001) *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Huynen M.M., Martens P., Schram D., Weijenberg M.P. & Kunst A.E. (2001) The impact of heat waves and cold spells on mortality rates in the Dutch population. *Environ Health Perspect*, **109**, 463-470.

IPCC (2000) *Emissions Scenarios. Summary for Policymakers. A special report of IPCC working group III.*

Kalkstein L.S. (2002) *Description of our heat/health watch-warning systems: their nature and extent, and required resources*. Center for Climatic Research, University of Delaware.

Kloner R.A., Poole W.K. & Perritt R.L. (1999) When throughout the year is coronary death most likely to occur? A 12-year population-based analysis of more than 220 000 cases. *Circulation*, **100**, 1630-1634.

Kovats R.S., Campbell-Lendrum D. & Matthies F. (2005) Climate change and human health: estimating avoidable deaths and disease. *Risk Anal*, **25**, 1409-1418.

Kovats R.S. & Kristie L.E. (2006) Heatwaves and public health in Europe. *Eur J Public Health*, **16**, 592-599.

Kunst A.E., Looman C.W. & Mackenbach J.P. (1993) Outdoor air temperature and mortality in The Netherlands: a time-series analysis. *Am J Epidemiol*, **137**, 331-341.

Le Tertre A., Lefranc A., Eilstein D., Declercq C., Medina S., Blanchard M. *et al* (2006) Impact of the 2003 heatwave on all-cause mortality in 9 French cities. *Epidemiology*, **17**, 75-79.

Mathers C.D. & Loncar D. (2006) Projections of global mortality and burden of disease from 2002 to 2030. *PLoS Med*, **3**, e442.

Messner T. (2005) Environmental variables and the risk of disease. *Int J Circumpolar Health*, **64**, 523-533.

Mokdad A.H., Bowman B.A., Ford E.S., Vinicor F., Marks J.S. & Koplan J.P. (2001) The continuing epidemics of obesity and diabetes in the United States. *Jama*, **286**, 1195-1200.

Morabito M., Modesti P.A., Cecchi L., Crisci A., Orlandini S., Maracchi G. *et al* (2005) Relationships between weather and myocardial infarction: a biometeorological approach. *Int J Cardiol*, **105**, 288-293.

Murray C.J. & Acharya A.K. (1997) Understanding DALYs (disability-adjusted life years). *J Health Econ*, **16**, 703-730.

Murray C.J., Lopez, A. D., Mathers, C.D., Stein, C. (2001) *The Global Burden of Disease 2000 project: aims, methods and data sources*.

Nogueira P.J., Falcao J.M., Contreiras M.T., Paixao E., Brandao J. & Batista I. (2005) Mortality in Portugal associated with the heat wave of August 2003: early estimation of effect, using a rapid method. *Euro Surveill*, **10**, 150-153.

Norris R.M. (2000) The natural history of acute myocardial infarction. *Heart*, **83**, 726-730.

Näyhä S. (2005) Environmental temperature and mortality. *Int J Circumpolar Health*, **64**, 451-458.

Pascal M., Laaidi K., Ledrans M., Baffert E., Caserio-Schonemann C., Le Tertre A. *et al* (2006) France's heat health watch warning system. *Int J Biometeorol*, **50**, 144-153.

R Development Core Team (2007) *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing Available At http://www.R-project.org.

Simon F., Lopez-Abente G., Ballester E. & Martinez F. (2005) Mortality in Spain during the heat waves of summer 2003. *Euro Surveill*, **10**, 156-161.

The Eurowinter Group (1997) Cold exposure and winter mortality from ischaemic heart disease, cerebrovascular disease, respiratory disease, and all causes in warm and cold regions of Europe. . *Lancet*, **349**, 1341-1346.

Uppala S.M., P.W. Kallberg, A.J. Simmons, U. Andrae, V. da Costa Bechtold, M. Fiorino *et al* (2005) The ERA-40 re-analysis. *Quart. J. Roy. Meteor. Soc.*, **131**, 2961-3012.

Table 1 *Age-standardized mean estimated AMI attack rate with 95% CI (assuming Poisson distribution with conjugate non-informative Gamma prior) in the seven studied municipalities of Finland by sex, for the study years 1983, 1988, and 1993*

	MEN						**WOMEN**					
	1983		**1988**		**1993**		**1983**		**1988**		**1993**	
Helsinki	700.8	(661.1; 740.7)	581.2	(545.8;618.4)	467.5	(437.4;498.7)	228.2	(210.6;247.1)	209.3	(192.0;227.3)	143.9	(129.9;158.4)
Kuopio	959.8	(823.8;1103.4)	688.7	(580.8;804.2)	501.9	(416.3;597.1)	282.2	(225.3;346.8)	199.0	(151.6;251.7)	179.3	(136.7;228.3)
Oulu	935.8	(802.1;1079.5)	677.7	(570.7;794.9)	470.1	(386.7;561.4)	231.8	(179.7;291.7)	256.3	(201.2;316.7)	146.2	(107.8;189.9)
Rovaniemi	850.1	(685.5;1035.3)	653.6	(518.7;804.8)	517.2	(404.8;644.3)	199.5	(131.6;279.8)	191.9	(129.0;266.9)	257.9	(186.3;340.2)
Tampere	678.1	(599.7; 761.0)	576.8	(508.3;650.3)	454.2	(397.9;514.8)	187.8	(156.1;221.4)	157.3	(129.1;188.0)	140.0	(114.2;169.1)
Turku	655.2	(578.1; 736.1)	576.2	(506.1;651.1)	468.4	(407.9;532.7)	175.4	(145.3;208.0)	139.0	(112.2;168.6)	124.3	(99.2;151.4)
Jyvaskyla	951.8	(819.1;1092.5)	661.7	(554.3;776.1)	529.1	(441.4;625.5)	243.5	(189.8;303.0)	244.5	(193.5;302.5)	154.3	(116.4;198.0)

Table 2a *Estimated regression coefficients for the full model (FW: Fourier series and daily weather) fitted for the first AMI. * p < .05*

	MEN			WOMEN		
	25-54	**55-64**	**65-74**	**25-54**	**55-64**	**65-74**
Intercept	-12.2699	-10.3164	-9.8237	-13.7108	-11.3175	-10.6376
Time	-0.0389*	-0.0414*	-0.0289*	-0.0648*	-0.0314*	-0.0239*
Mean temperature	0.0027	0.0087	-0.0113	-0.0307	-0.0162	0.0059
Mean temp. squared	0.0003	-0.0005	-0.0005	-0.0014	-0.0009	0.0008
Pressure rate	0.0191	0.0004	-0.0098	0.0144	0.0176	0.0015
Pressure rate squared	0.0077	-0.0041	-0.0009	0.0085	0.0081	-0.0033
Wind speed	-0.0180	-0.0209	0.0007	-0.0186	-0.0229	-0.0206*
Variation of temp. during the last 7 days	0.0026	0.0155	0.0218	0.0194	-0.0453	0.0220
Fourier terms (x: fraction of the year; W: fraction of the week)						
sin(2π1x)	0.0229	0.0242	-0.0775	-0.1142	-0.1624	0.0565
sin(2π2x)	-0.0832	0.0583	0.0134	0.0772	-0.0248	-0.0192
sin(2π3x)	-0.0181	-0.0675	0.0091	0.0189	0.0251	-0.0368
sin(2π4x)	-0.0093	-0.0665	0.0040	0.1215	-0.0064	0.0143
sin(2πW)	0.0562	0.0592	-0.1124*	-0.0109	-0.0633	0.0579
cos(2π1x)	-0.0091	0.0153	-0.1767	-0.4511	-0.1539	0.2139*
cos(2π2x)	-0.0313	0.0227	-0.0385	0.0074	-0.0325	-0.0832
cos(2π3x)	-0.0391	-0.0375	-0.0685*	-0.0569	-0.0027	-0.0141
cos(2π4x)	0.0331	-0.0152	-0.0140	0.0216	-0.0744	-0.0341
cos(2πW)	0.0188	-0.0584	-0.0795*	-0.1948*	-0.0355	-0.0398

Table 2b *Estimated regression coefficients for the full model (FW: Fourier series and daily weather) fitted for the recurrent AMI. * p < .05*

	MEN			WOMEN		
	25-54	**55-64**	**65-74**	**25-54**	**55-64**	**65-74**
Intercept	-14.6407	-12.0619	-10.6429	-17.8767	-13.1429	-11.4482
Time	-0.0935*	-0.0703*	-0.0563*	-0.1191	-0.1059*	-0.0611*
Mean temperature	0.0398	0.0158	0.0190	0.0717	0.0234	0.0050
Mean temp. squared	-0.0022	0.0004	0.0001	0.0006	0.0010	0.0001
Pressure rate	0.0759	0.0199	0.0146	-0.3074	0.0466	-0.0697*
Pressure rate squared	-0.0653*	0.0070	-0.0041	0.1026*	0.0157	-0.0046
Wind speed	-0.0065	-0.0147	-0.0392*	-0.2974	-0.0746	-0.0432*
Variation of temp. during the last 7 days	0.1741*	0.1305*	0.0337	-0.1608	-0.0450	-0.0480
Fourier terms (x: fraction of the year; W: fraction of the week)						
sin(2π1x)	0.2198	-0.0102	0.1767*	0.0968	0.1000	0.0853
sin(2π2x)	-0.0843	-0.0103	-0.0928	2.5641	0.4858*	0.0987
sin(2π3x)	-0.0510	-0.0828	-0.0678	-0.0291	0.1530	-0.1386
sin(2π4x)	0.0411	0.1339	0.0646	1.3994	0.2801	-0.0897
sin(2πW)	-0.0229	0.0085	-0.0968	1.0629	-0.0820	0.0163
cos(2π1x)	0.0714	0.2523	0.2827	0.7391	0.2553	0.1725
cos(2π2x)	0.1379	-0.1012	-0.0658	-1.3481	-0.0266	0.0147
cos(2π3x)	-0.0512	0.0760	0.0446	-0.8004	-0.0150	0.1028
cos(2π4x)	-0.1431	0.0293	-0.0684	0.3076	0.0556	-0.1619*
cos(2πW)	-0.0752	-0.0236	0.0644	-0.6568	-0.1659	-0.0468

Table 3 *Mean squared errors (MSEs) corresponding to 1-out and 5-out cross-validation of the four models; LT: Linear trend, FS: Fourier series, DW: Daily weather, FW: Fourier series and daily weather*

			1-out				5-out			
			LT	**FS**	**DW**	**FW**	**LT**	**FS**	**DW**	**FW**
1st AMI	**Men**	**25-54**	0.1866	0.1871	0.1869	0.1877	0.1867	0.1872	0.1871	0.1878
		55-64	0.2239	0.2241	0.2241	0.2248	0.2241	0.2243	0.2243	0.2249
		65-74	0.2479	0.2470	0.2483	0.2473	0.2480	0.2472	0.2484	0.2474
	Women	**25-54**	0.0331	0.0333	0.0333	0.0334	0.0332	0.0334	0.0333	0.0335
		55-64	0.0824	0.0826	0.0825	0.0826	0.0824	0.0826	0.0825	0.0826
		65-74	0.2070	0.2071	0.2076	0.2075	0.2071	0.2072	0.2077	0.2076
Recurrent AMI	**Men**	**25-54**	0.0195	0.0196	0.0195	0.0195	0.0195	0.0196	0.0195	0.0196
		55-64	0.0572	0.0575	0.0573	0.0575	0.0573	0.0576	0.0573	0.0576
		65-74	0.0987	0.0990	0.0987	0.0991	0.0987	0.0991	0.0988	0.0992
	Women	**25-54**	0.0009	0.0009	0.0010	0.0009	0.0009	0.0009	0.0010	0.0009
		55-64	0.0113	0.0114	0.0113	0.0114	0.0113	0.0114	0.0113	0.0114
		65-74	0.0535	0.0536	0.0534	0.0535	0.0536	0.0536	0.0535	0.0536

Figure 1 *The seven city areas of Finland involved in the study*

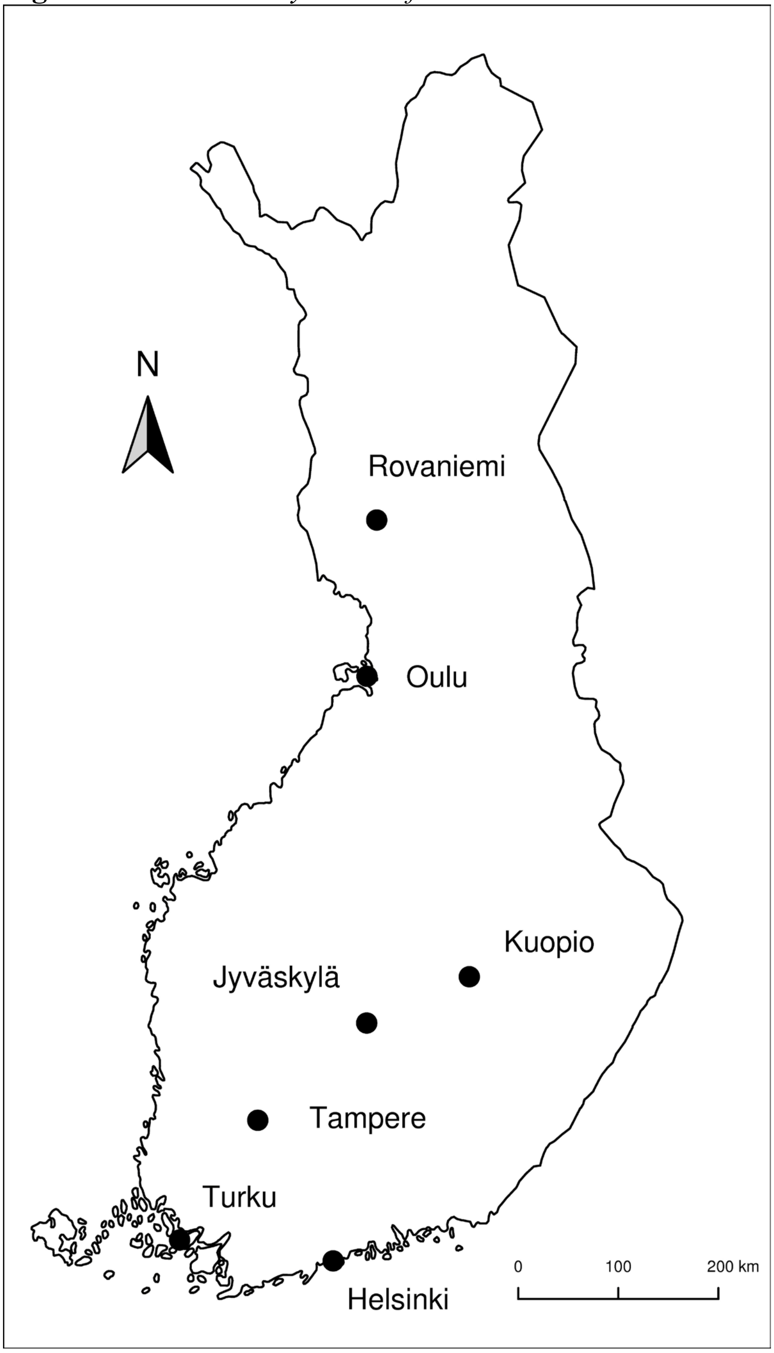
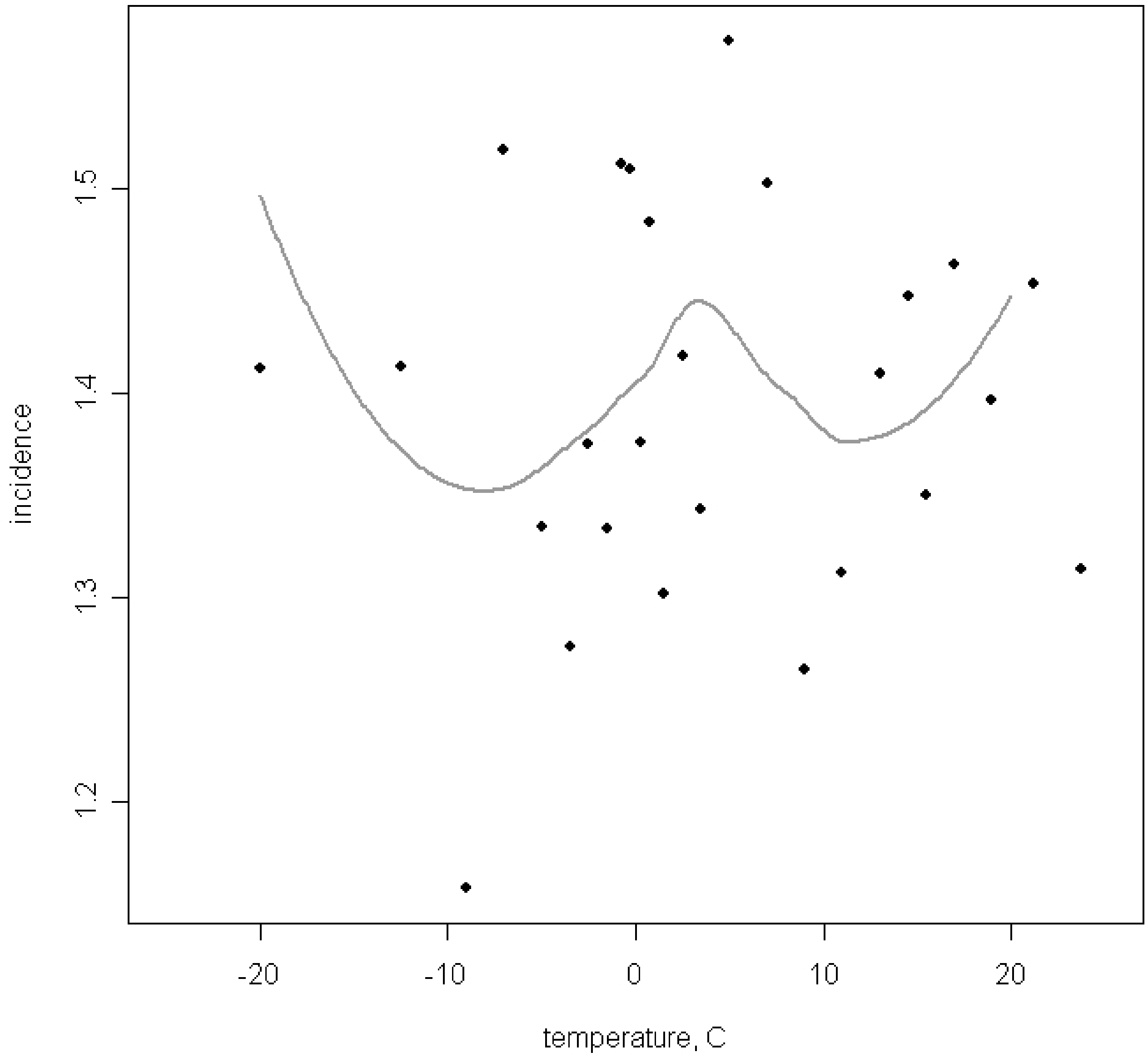


Figure 2 *Observed dependence of average daily incidence per 100'000 persons on the daily temperature*



The Value of Observations in Determination of Optimal Vaccination Timing and Threshold

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Abstract – The WHO report on the global and regional burden of disease and risk factors in 2001 lists meningitis among the ten leading causes of disease-adjusted life years loss. A vaccine is available for some, but not all of the strains of meningococcal meningitis. Although the WHO provides guidelines on recognizing an epidemic, there is some discussion with regard to their usability and optimality. We use computer simulation based on the Susceptible-Infected-Recovered (SIR) stochastic dynamic model to examine the useful epidemic threshold. The model parameterization is based on the data available from publications. In addition we consider impact of auxiliary information such as weather observation and prediction, since higher incidence of meningitis appears to coincide with certain climatic events. As our experiments show, information on the timing of these events is a major factor in the determination of the optimal vaccination response.

Keywords: meningococcal meningitis, stochastic simulations, dynamic modeling, weather, SIR model.

1. INTRODUCTION

According to the report on the global and regional burden of disease and risk factors in 2001, the ten leading causes of disease in low-and-middle income countries were broadly similar to those for the world as a whole, and included five communicable diseases (Murray, 1997). In sub-Saharan Africa, infectious and parasitic diseases (excluding HIV/AIDS and including respiratory infections) were responsible for over 200 disease-adjusted life years per 1000 population. One of these diseases is meningococcal meningitis, which remains a major cause of mortality in sub-Saharan Africa, despite the availability of the meningococcal polysaccharide vaccine (Robbins, 2003).

Preventive vaccination of some proportion of the total population helps reduce the disease pool considerably. At any rate, it should be implemented early enough in the epidemic, to have a meaningful effect. The decision-maker is faced with a choice of buying vaccine early and, perhaps, wasting money and loosing political credibility due to, e.g. side-effects of the vaccine or non-event, or buying late, when the epidemics is confirmed and losing valuable human lives to death and/or disability resulting from earlier inaction. The question thus becomes one of optimization: when is it worth to take measures or, to put it in other words, what is the useful epidemic threshold. Recognizing an epidemic is often problematic mainly due to the endemic nature of many diseases, meningococcal meningitis included, as well as to the poor monitoring capabilities. Guidelines are provided by the WHO, but there is some disagreement with regard to their usability and optimality (Robbins, 2003).

We approach this question from a stochastic dynamic modeling point of view and apply a suitable augmentation of a standard Susceptible-Infected-Recovered (SIR) model (Tucker, 2006) to a simulated population. We consider a single epidemic event, parameterized in accordance with the epidemiological data available on meningococcal meningitis, and use numerical simulation to study the effect of various vaccination thresholds on the epidemics dynamics. We also consider the potential usefulness of auxiliary information. For example, it has recently been suggested (Roberts, 2008) that the epidemics of meningococcal meningitis in the Sahel area correlate with the dust storms. We discuss the effect of including such data into analysis with the view to illustrate the possible benefits of GEOSS to the solution of this human health challenge.

2. MODEL

2.1 Susceptible – Infected – Recovered Model

We formulate our model following (Tucker, 2006). At any given time point, every individual in the population of size $n(t)$ falls into one of the three state categories: *susceptible* (S), *infected* (I), and *recovered* (R). Here, recovered also means forever immune. However, in case of meningitis, fatality resulting from an epidemic is non-negligible. It affects the population size, which can therefore no longer be assumer constant. Therefore we introduce an additional variable to be monitored, $D(t)$ – total death toll up to and including time t. Note that $D(t)+n(t)=n(0)$. The population is assumed to be homogeneous, i.e., the probability of becoming infected from another infected individual (π) does not vary from person to person and the probability of a susceptible individual becoming infected at time t is

$$p(t) = 1 - \left(1 - \frac{\pi(t)I(t)}{n(t)-1}\right)^N \qquad (1)$$

where $I(t)$ is the number of currently infected individuals in the population and N is the number of contacts each individual has. Once infected, a patient may recover within any week with probability γ, die from the disease with probability μ or stay infected with probability $1-\gamma-\mu$, $\gamma+\mu\leq 1$.

The general stochastic dynamics framework may be described as

$$S(t) = S(t-1) - I.new(t-1) - u(t)\alpha S(t-1) \qquad (2.1)$$
$$I(t) = I(t-1) + I.new(t-1) - D.new(t-1) - R.new(t-1) \qquad (2.2)$$
$$R(t) = R(t-1) + R.new(t-1) + u(t)\alpha S(t-1) \qquad (2.3)$$
$$n(t) = n(t-1) - D.new(t-1) \qquad (2.4)$$

where *I.new*, *D.new*, and *R.new* are the newly infected, dead and recovered individuals respectively. In the stochastic framework we generate these from the binomial and multinomial distributions, as follows:

$$I.new(t) \sim Bin(S(t),p(t)) \quad (2.5)$$

$$\{R.new(t), D.new(t), I(t)-R.new(t)-D.new(t)\} \sim Multinomial(I(t), \{\gamma, \mu, 1-\gamma-\mu\}) \quad (2.6)$$

The binomial distribution in Equation 2.5 randomly selects new cases of infection from the susceptible population. The multinomial distribution in Equation 2.6 randomly sorts those who are currently ill into diseased, recovered and still infected. Finally, we assume that for a constant proportion (δ) of those recovered infection results in serious sequelae.

The control variable $u(t)$ in Equations (2.1) and (2.3) equals 1 if the mass vaccinations is conducted at time t, and is 0 otherwise. Here, the vaccination is done only once during the study period, when the number of newly infected individuals stays above the threshold for two consecutive weeks for the first time. As a result, α% of the currently susceptible population becomes immune.

2.2 Optimization

The current WHO approach (ICG, 2008) uses population-based weekly incidence rates to determine whether the meningitis disease has reached alert (5/100000), epidemic (10/100000), or outbreak levels (15/100000). In order to produce the comparable decision rules we assume that the vaccination threshold (i.e., the incidence level which has to be reached for the mass vaccination to be ordered) is set exogenously. Our aim is to select the optimal vaccination threshold such that the expected total costs of an epidemic up to the time horizon T are minimized:

$$\sum_{t=0}^{T} \frac{1}{(1+\rho)^t} \{u(t)\, c^{vacc}\, \alpha\, S(t) + c^{treat}\, I(t) + c^{dead}\, D.new(t) + c^{seq}\, \delta\, R.new(t)\} \quad (3)$$

Here parameter ρ stands for the discount rate, c^{vacc} denotes the costs of vaccinating one individual, c^{treat} is the weekly cost of treatment per one infected individual, c^{dead} stands for the lump sum of the costs associated with death (e.g. loss of breadwinner of the family) and c^{seq} denotes the lump sum of the sequelae costs, including life-long disability.

2.3 Weather

We demonstrate the benefits of auxiliary information regarding the weather event in the following experiment. Assume that the parameter $\pi(t)$ in Equation 1 remains constant, $\pi(t) = \pi^0$, until the climate event occurs at time t'. Afterwards $\pi(t)$ jumps abruptly to a new value π^1. We assume that $\pi^1 > \pi^0$, i.e. the climate event makes the disease more infectious. We consider the following response scenarios:

Perfect Forecast (PF): We are equipped with full information (t' and π^1) concerning an event occurrence, so we can state optimal vaccination rules before and after the event occurrence.

Scenario 1 (S1): We ignore the occurrence of the event completely and select the optimal threshold according to the probability π^0.

Scenario 2 (S2): We anticipate the event but are not able to predict its exact timing and, preferring to err on the side of caution, determine the optimal threshold according to probability π^1 for the whole period.

Scenario 3 (S3): We base our strategy on the available weather forecast, which predicts that an event will occur at time t*, t*< t'. Alternatively, not willing to wait till the last moment, we prefer to change vaccination policy early rather than too late.

Scenario 4 (S4): We anticipate an event happening at time t*, t*> t'. Another interpretation here is an event occurring suddenly at time t', and it takes t*-t' time to adjust vaccination strategy.

Note, that S1 is a special case of S4 for $t^* \rightarrow \infty$. Similarly, setting t*=0 makes scenario S3 match S2.

2.4 Parameterization

We consider one week as the smallest discrete unit of time, since this is the highest resolution at which data become available and at which decision-making is likely to be conducted. We have set μ=0.0265 and γ=0.2382 which correspond to 10% case-fatality (i.e. 10% of all those infected die) and an average 2.5 weeks of recovery per infected person. These parameter values are derived analytically from modelling assumptions. Throughout simulations, we have determined that $N\pi \approx 0.26$ guarantees an attack rate of 250 to 1000 per 100,000 and an average duration of 30 weeks per epidemics, which is similar to observed epidemics. Here, the duration of an epidemic is defined as the number of weeks from initialisation of the epidemic (I(0)=2) to the first week t reaching I(t)=0. We have thus chosen N=5 and considered a range of values of π around 0.05. For the weather event simulations, we have assumed π^0=0.05, π^1= 0.07, t'=10 and in S3 and S4 we set t* to be the 5th and 20th weeks respectively.

The simulations have been run for the initial population of 100,000. When vaccination is performed, α=80% of the currently susceptible population become immune. The values of the cost parameters c^{vacc} and c^{treat} follow estimations in Bovier et al (1999). Parameters c^{dead} and c^{seq} were set in accordance with preliminary sensitivity analysis (not reported here). Discount rate is set to ρ=3%.

3. RESULTS

Figure 1 illustrates the dependence of the expected epidemic toll (the total number of cases) on the vaccination threshold (cases per 100,000/week) for different values of the individual contagion probability π. The outcome is apparently highly sensitive to the value of π, which underlines the importance of precise knowledge of this parameter to the epidemic control. The relationship is almost linear for the smaller values of π and reaches a plateau for higher values because the weekly incidences never reach such a threshold. In Figure 1 the thick black line is a spline through estimated optimal vaccination thresholds. One can see that when the optimal threshold is applied, the resulting toll remains fairly stable over various values of π. The optimal vaccination threshold,

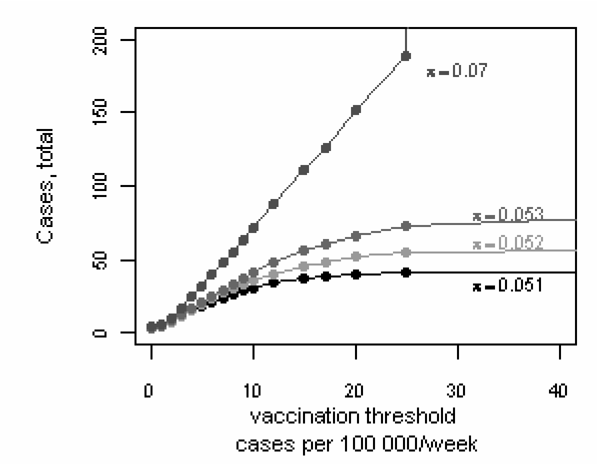

Figure 1. Epidemics toll as a function of vaccination thresholds for various individual contagion probabilities π.

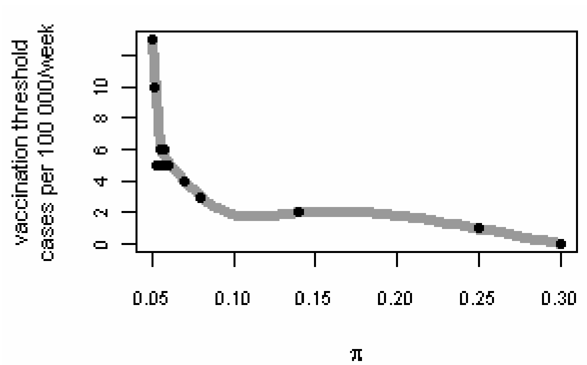

Figure 2. Optimal vaccination threshold as a function of individual contagion probability π.

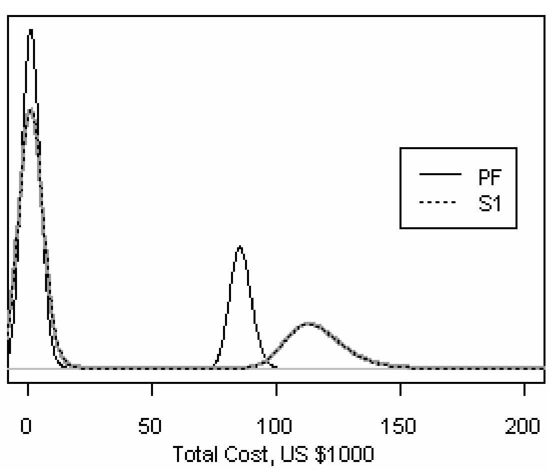

Figure 3. Estimated density function of the total cost resulting when the optimal vaccination threshold is determined under full information on the contagion probability (solid curve) and under deficient information (dashed line).

on the other hand, may be highly sensitive to the assumed contagion probability, as illustrated by Figure 2.

Figure 3 shows difference in the resulting total costs under information scenarios PF and S1 (see Section 2.3). The distribution of costs generally is bimodal with the first peak corresponding to the simulation runs where no epidemics happens due to low contagiousness, and the later peak for the simulations where the disease does reach epidemic proportions and vaccination is performed. The distribution under the scenario S1 is more concentrated to the right than that under the PF scenario. This demonstrates the value of information: setting the vaccination rules without reliable information on contagious probability increases the expected total costs. Furthermore, under scenario S1 there is more uncertainty with regard to the outcome.

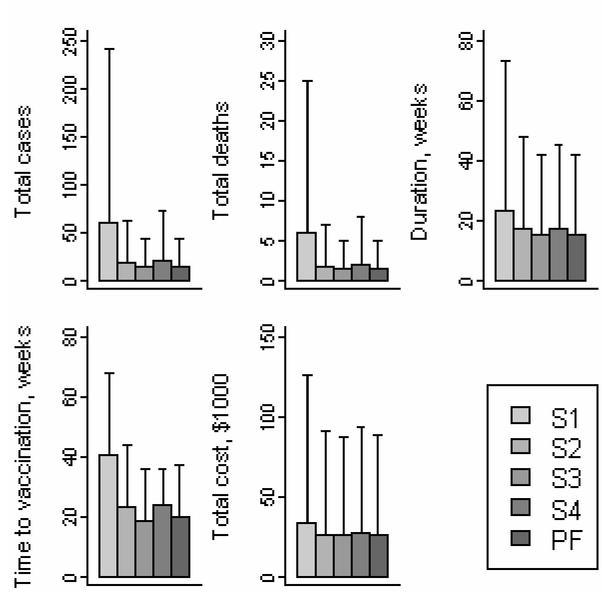

Figure 4. Expected values and the 95% quantile of the disease toll, number of deaths, epidemics duration, vaccination time and total costs under the different information scenarios described in Section 2.3.

As Figure 4 shows, scenario S1 results in the worst response: the disease and death toll, the duration of epidemics and the total costs are all noticeably higher than under PF scenario. The results for Scenario S2 show that an unnecessarily early switch of the threshold increases the disease toll by over 25%. On the other hand, the switch of the vaccination rules almost immediately before the event (S3) results in an outcome comparable to the PF scenario: a slight decrease in disease toll is compensated for by increase in total costs. However, the after-event-response (S4) leads to the increase in both: disease toll (by more than 40%) and the expenditure. The vaccination time* is determined by the response strategy chosen: the less contagious the disease is assumed to be, the higher the optimal threshold and, consequently, the later the vaccination time. A time shift of the jump in the

* only simulations where mass vaccination was performed are included in calculation

contagious probability value has negligible effect on the optimal threshold pair.

4. DISCUSSION

In this study so far, we have considered optimising vaccination strategy in terms of endogenously set decision rules. The optimal decision rule was found to be highly sensitive to the parameter π, which describes the individual contagion probability. This means that dynamic decision-making with a learning mechanism might considerably improve the outcome of an epidemic. In the future we plan to compare these results to the optimal strategy determined by applying the real options approach and to show the possible weaknesses of the presented scenarios type of analysis.

Roberts (2008) suggests a connection between the dust storms in Sahel and meningitis epidemics. Although, the exact mechanism, which might cause this, is unclear, in very general terms this might be modeled as a sudden jump in the value of π. Thomson et al (2003) conclude that environmental models may make predicting epidemics feasible. Molesworth et al (2003) have quantified the relationship between absolute humidity, dust, rainfall, land cover type and population density, and the geographical distribution of epidemics with 83% sensitivity and 67% specificity. As our own simulations show a major factor in the determination of the optimal vaccination response is information concerning the event occurrence in the period in question. Further information on event occurrence timing help manage the disease spread better and contributes to our prediction of epidemic dynamics. Hence, the Global Earth Observation System of Systems (GEOSS) has an important role to play in combining environmental and epidemiological data in real time for the improved decision-making.

Some epidemics models explicitly consider carriage as a separate stage of a disease. A carrier is often contagious, but may remain healthy, and may then either become immune or revert to the susceptible pool. In our case, the information on various aspects of carriage (such as duration of carriage, probability of contagion from a carrier versus from an ill person, etc.) is so scarce, that explicit consideration would merely add a completely latent, i.e. unobservable, layer to the model and thus not aid our understanding of the phenomena.

The assumption of homogeneous population is clearly a simplification, and explicit consideration of social structural hierarchy and mixing should be introduced into the model. Also, *N. meningitides* can be classified into 13 serogroups, of which the serogroup A accounts for most epidemics in the African meningitis belt (Leimkugel, 2007). The vaccines are strain-specific, although there exist quadrivalent vaccines. This means, that although our model assumes exact knowledge with respect to strain and unlimited availability of vaccine against it, in practice, not all epidemics are amenable to vaccination and also some time should be spent on determining the correct strain to vaccinate against.

The cost of treatment and vaccines is measured in dollars, the toll of the epidemics is measured in human lives and disability. The attempts to assign a monetary value to human life have remained few, controversial and largely unhelpful. An index which compares, for example, the cost per life saved (see, e.g., Brunovsky, 2009) might be a better object of optimization.

To conclude, although further work is needed to make our simplified model more realistic, the initial results highlight the importance of information with regard to contagion probability on the optimal vaccination threshold.

REFERENCES

P. A. Bovier, K. Wyss, H. J. Au, “A cost-effectiveness analysis of vaccination strategies against N.meneingidis meningitis in sub-Saharan African countries”,Social Science and Medicine vol 48, p. 1205-1220, 1999.
P. Brunovský, D. Ševčovič, J. Somorčík, D. Hroncová, K. Pospíšilová, “Socio-economic impacts of pandemic influenza mitigation scenarios in Slovakia” , To appear in Journal of Economics, 2009.
International Coordinating Group on Vaccine Provision for Epidemic Meningitis Control (ICG), 2008. “Guidelines for applying to the emergency stockpile”. http://www.who.int/csr/disease/meningococcal/ICG_guidelines_2008_02_09.pdf
J. Leimkugel, A. Hodgson, A. A. Forgor, V. Pflueger, J.-P. Dangy, T. Smith et al, “Clonal waves of *Neisseria* colonization and disease in the African Meningitis Belt: eight-year longitudinal study in Northern Ghana,” PLoS Med, vol 4., p. e101, 2007.
C.J. Murray and A. D. Lopez, “Global mortality, disability, and the contribution of risk factors: Global Burden of Disease Study,” Lancet, vol 349, p.p. 1436-1442, May 1997.
J. B. Robbins, R. Schneerson, E.C. Gotschlich, I. Mohammed, A. Nasidi, J.P. Chippaux, et al, “Meningococcal meningitis in sub-Saharan Africa: the case for mass and routine vaccination with available polysaccharide vaccines,” Bull World Health Organ, vol 81, p.p. 745-750; with discussion: p.p. 751-755, 2003.
A. M. Molesworth, L. E. Cuevas, S. J. Connor, A. P. Morse, and M. C. Thomson, “Environmental risk and meningitis epidemics in Africa,” Emerg Infect Dis, vol. 9, p.p. 1287-1293, 2003.
L. Roberts, “Infectious disease. An ill wind, bringing meningitis,” Science, vol 320, p.p. 1710-1715, 2008.
M. C. Thomson, A. M. Molesworth, D. H. Mamoudou, K. R. Yameogo, F. Belanger, and L. E. Cuevas, “Potential of environmental models to predict meningitis epidemics in Africa,” Trop Med Int Health, vol 11, p.p. 745-750, 2003.
H.C. Tuckwell and R. J. Williams, “Some properties of simple stochastic epidemic model of SIR type,” Math Biosci, vol 208, p.p. 76-97, July 2007.’

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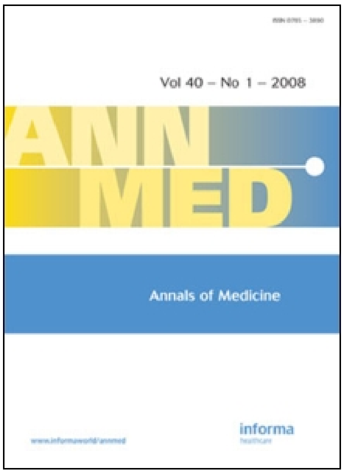

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Temporal variation in case fatality of acute myocardial infarction in Finland

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ORIGINAL ARTICLE

Temporal variation in case fatality of acute myocardial infarction in Finland

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Abstract

Background. Previous studies have suggested that seasonal variation and weather conditions have an influence on the incidence and mortality of acute myocardial infarction (AMI). The influence of these factors on AMI case fatality is less studied.

Aims. The aim of this study was to examine the temporal variation of AMI case fatality and the effect of daily weather conditions on it.

Methods. We analysed death registry and hospital discharge data from all men and women ($n = 7328$) with their first AMI occurrence in the seven largest cities in Finland in the years 1983, 1988, and 1993, aged 25 to 74 years.

Results. The mean annual 28-day case fatality was 44%. We found significant weekly and monthly variation of case fatality ($P < 0.001$). The December holiday season had the highest case fatality throughout the year in women and men aged 65–74 years ($P < 0.05$). The highest weekly case fatality was on Sundays; it differed significantly from the rest of the weekdays only for the oldest age-group (64–74) ($P < 0.01$).

Conclusions. There is significant weekly and monthly variation in case fatality of AMI. The highest case fatality risk for AMI is during the Christmas season and on Sundays. Weather conditions were not found to have an effect on the case fatality.

Key words: *Case fatality rate, meteorological factors, myocardial infarction, seasons*

Introduction

It is well recognized that human health is influenced by environmental factors such as weather conditions and season (1–3). A large number of studies have shown the impact of these factors on mortality, particularly due to respiratory and cardiovascular diseases (2,4–8). In developed countries, coronary heart disease (CHD) is the leading cause of death and disability, measured in disability-adjusted life years (DALYs) (9,10). The World Health Organization (WHO) predicted an even further increase in CHD prevalence by the year 2030, mainly due to the expected population ageing, growing world affluence, increase in the prevalence of type 2 diabetes and obesity, as well as climate change (9,11–13). The major clinical manifestations of CHD are acute myocardial infarction (AMI) and sudden death.

The influence of weather conditions and season on the incidence of AMI has been widely studied primarily in association with temperature and air pressure changes and wind activity (1,3,14–17). The influence of season and weather conditions on AMI mortality, on the other hand, has been focused upon only in a small number of studies (18–21). However, the results are difficult to interpret since it is impossible to distinguish whether the observed pattern of variation is due to incidence or case fatality. The only published study, to our knowledge, on case fatality and season divided the data into four seasons and found a winter peak in case fatality (22).

The climate in Finland is primarily influenced by its geographical position, being one of the northernmost countries in the world. There are both maritime and continental influences. Due to

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Key messages

- There is significant weekly and monthly variation in case fatality of acute myocardial infarction (AMI).
- There is no statistically significant effect of daily weather conditions on case fatality of AMI.
- The highest case fatality risk for AMI is during the Christmas season and on Sundays.

Abbreviations

AMI	acute myocardial infarction
CDS	Cause of Death Statistics
CHD	coronary heart disease
DALY	disability-adjusted life year
HDR	Hospital Discharge Registry
ICD	International Classification of Diseases
MSE	mean squared error
WHO	World Health Organization

Regression models:

NT	incl. age and sex only
LT	incl. age, sex, and linear trend
FS	incl. age, sex, and seasonal Fourier terms
W0	incl. age, sex, and weather covariates
WS	incl. age, sex, seasonal Fourier terms, and weather covariates

this continental influence and the Gulf Stream, the average temperature is several degrees higher than in other areas of the same latitude. Winters are rather cold and summers comparatively hot, and weather types can change quickly, as Finland lies in the transition zone from tropical to polar air masses. For this study, the seven largest Finnish city areas have been chosen: Helsinki, Turku, Jyväskylä, Tampere, Kuopio, Oulu, and Rovaniemi. The climate characteristics for these city areas are similar but differ in certain aspects like weekly variation of temperature and wind strength. The mean temperature follows approximately the geographical position of the cities, being coldest in the north and warmest in the south. The mean winter temperatures differ more from city to city than the summer ones.

In this study we examine the effect of season and weather conditions on the 28-day case fatality of AMI by calculating the case fatality rates of the years 1983, 1988, and 1993 by month and testing them for seasonality. In addition, we compare five statistical models: one with and one without a linear trend, one with a weather component, one with a periodic seasonal component, and one with both a weather and seasonal component. Both the goodness-of-fit and the predictive properties of these models are compared.

Patients and materials

The data consist of all AMI patients in Finland in 1983, 1988 and 1993. The data were obtained from two nationwide registries: the Cause of Death Statistics (CDS) maintained by Statistics Finland and the Hospital Discharge Registry (HDR) maintained by the National Research and Development Centre for Welfare and Health. The computerized record linkage of the two data sets was performed by using the personal identification number assigned to all Finnish residents, in order to obtain the deaths and hospitalizations due to AMI in Finland for those years (International Classification of Diseases ICD-9 codes 410–414). The place of residence of the AMI cases was set by the municipality of the patient at time of diagnosis, and the sex-age-municipality-specific population data were obtained from Statistics Finland. The linkage also made it possible to distinguish between first and recurrent events of AMI: in order to do this the HDR was checked for any previous mention of AMI. For this study, we only considered patients with the first recorded occurrence of AMI. The event was considered fatal if the death had occurred either out of hospital or within 28 days of arrival in the hospital. The overall sensitivity of the ICD codes for MI in the combined HDR and CDS was earlier found to be 83% and the positive predictive values 90% for certain areas of Finland (23). Mähönen et al. (24) found the corresponding agreement in diagnosis to vary from 87% to 100% for the ICD codes 410–414.

The weather data were obtained from the European Centre for Medium-Range Weather Forecasts ERA-40 project (25,26). It consists of interpolated measurements for air temperature, pressure, and wind speed projected at 6-h intervals for a $2.5^\circ \times 2.5^\circ$ grid worldwide. Comparison with locally available meteorological data for the cities Helsinki and Oulu showed high correlation.

The geographical positions for the seven cities selected for this study are the following: Helsinki (60.2N, 24.9E), Kuopio (62.5N, 27.4E), Oulu (65.0N, 25.3E), Rovaniemi (66.3N, 25.4E), Tampere (61.3N, 23.5E), Turku (60.3N, 22.2E), and Jyväskylä (62.1N, 25.4E) (Figure 1). The population at risk for the three study years was in total 1,319,964 men and 1,508,634 women.

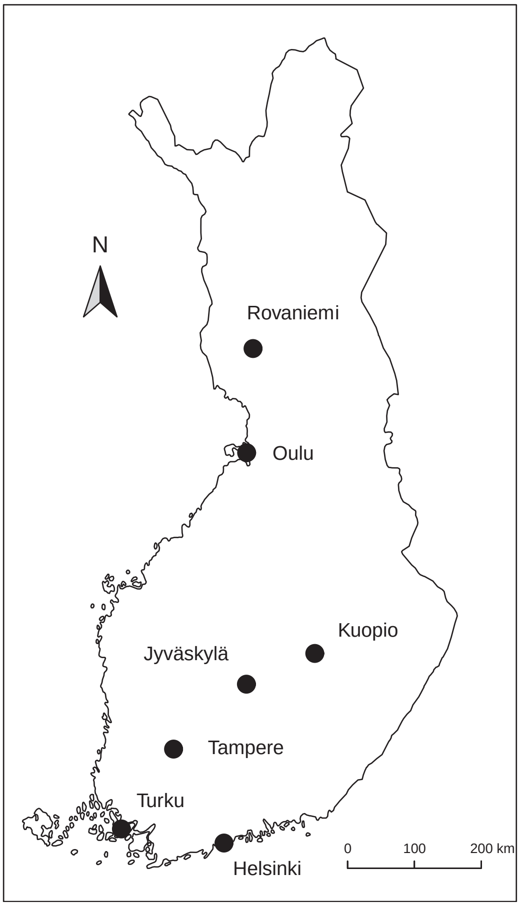

Figure 1. The study area includes the seven largest cities of Finland.

Methods

In the analysis, the time of event was taken to be either the time of hospital admission (if the case data came from the HDR) or the time of death (if the case data came from the CDS). The weather variables were evaluated relative to the time of event.

The monthly and weekly 28-day case fatality rates were tested for seasonality, by comparing the fit of binomial regression with a logit link, adjusted by sex and age, with and without month and weekday factors, respectively.

Five regression models of increasing complexity have been fitted: a model with covariates on sex and age only (NT), one with a linear trend (LT), a model with seasonal Fourier terms (27) which includes up to four harmonics and an additional weekday harmonic (FS), a model with daily weather covariates and no seasonal effects (W0), and a model with both Fourier terms and weather covariates (FW).

The daily case fatality was assumed to follow a binomial distribution, and only the days with at least one case of AMI were included in the analysis.

The preliminary graphical analysis indicated that case fatality increases with age in an almost linear fashion. The cross-term for age and sex was also included since it proved to be significant ($P=0.03$). On the other hand, the linear time trend term was included in the LT model only, since it proved to be non-significant ($P=0.71$). The optimum number of harmonics was assessed using the method described in Hunsberger et al. (28), and all five harmonics were thus included in the model. The weather covariates finally included in the W0 and FW models were the daily temperature and its square.

The predictive properties of the model were assessed through a one (day)-out cross-validation (29), for which the mean squared errors (MSE) were evaluated. A smaller MSE indicates better predictive power for the model.

The statistical analysis was performed using R-programming environment (30).

Results

A total of 7328 cases of the first AMI occurrence were registered in the years 1983, 1988, and 1993. The overall 28-day case fatality was 44%, because 3196 subjects died within 28 days of the diagnosis. The case fatality increased with age but did not differ significantly between the years under study (see Table I). Variation by month and by day of the week was statistically significant with $P<0.001$. The observed case fatality percentages are shown in Figure 2 and 3. The corresponding distributions of first AMI incidence are given in the background for comparison.

Only the average weekly temperature and its square were finally included in the weather model based on the stepwise selection algorithm, starting with the model which included wind speed and atmospheric pressure rate, both linear and squared. The coefficients for the five fitted models are shown in Table II. Since the binomial regression model requires a logit link, these coefficients are not directly interpretable beyond the direction of the effect.

The cross-validation analysis indicated that the best prediction of case fatality is provided by a model with temporal effects but without weather covariates (model FS, Table II). However, the differences in mean squared errors (MSE) of all the non-trivial models were small compared to the trivial no trend (NT) model. Therefore, neither the temporal variation nor information on weather is of use in the prediction of case fatality.

December proved to be the month with the highest observed fatality for women and for men 65–74 years of age (see Table III and Figure 2). Although the case fatality rates for the month with

Table I. First acute myocardial infarction (AMI) case fatality rates by sex, year, and age-group in Finland.

	25–54 years old		55–64 years old		65–74 years old	
Year	Death/cases	Rate	Death/cases	Rate	Deaths/cases	Rate
Men						
1983	165/521	32% (28%; 36%)	280/608	46% (42%; 50%)	378/675	43% (52%; 60%)
1988	140/462	30% (26%; 35%)	246/575	43% (39%; 47%)	318/574	55% (51%; 60%)
1993	136/403	34% (29%; 38%)	183/470	39% (35%; 43%)	335/598	56% (52%; 60%)
Women						
1983	23/95	24% (16%; 33%)	75/224	34% (27%; 40%)	269/593	45% (41%; 49%)
1988	17/87	20% (11%; 28%)	78/207	38% (31%; 44%)	267/545	49% (45%; 53%)
1993	13/56	23% (12%; 34%)	52/175	30% (23%; 37%)	221/460	48% (43%; 53%)

the highest risk did not differ significantly from the next highest risk month in any sex-age-group, they were significantly higher ($P < 0.05$) than the average for the rest of the year for all except the middle-aged men. Furthermore, the Christmas season, defined each year as 23rd to 31st of December, proved the most risky of all, with significantly higher case fatality rates for all except young men (25–54) and older women (65–74) ($P < 0.05$).

The weekday distribution was more uniform. Sunday was found to be the highest case fatality day of the week. Sunday estimates were significantly higher than the average for the rest of the week only for the age-group 65–74 for both sexes ($P < 0.1$).

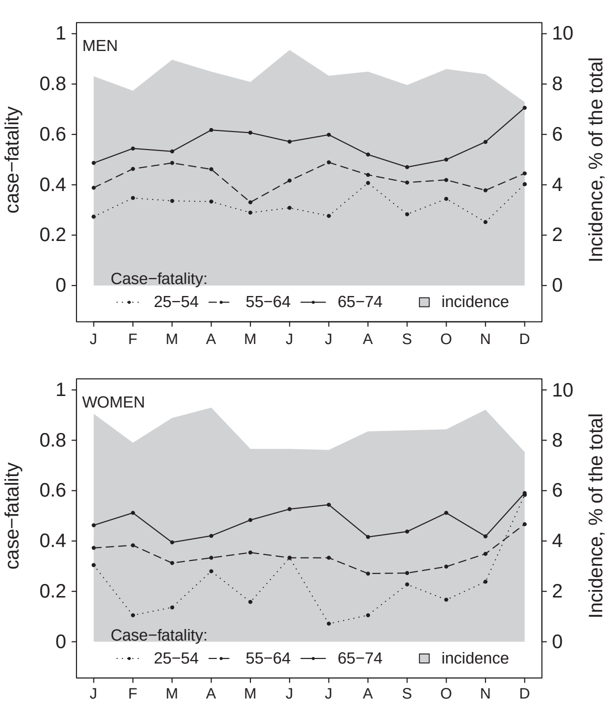

Figure 2. Monthly variation of first acute myocardial infarction (AMI) incidence and first AMI case fatality rates by age-group and sex for the years 1983, 1988, and 1993.

Discussion

We studied the temporal variation in case fatality of AMI with weather conditions and season using 7328 Finnish cases of first AMI occurrence, of both sexes, aged 25–74 years in the years 1983, 1988, and 1993. We found significant weekly and monthly variation of case fatality. The weather components used did not add significantly to the model.

Due to the lack of data we could not investigate case fatality among patients over 75 years old. Therefore the results cannot be generalized for older age-groups.

The temporal variation of case fatality due to AMI is not well studied. Most of the studies focus on the seasonality of AMI mortality (18,19). The seasonal variation of AMI mortality is hard to interpret. It is

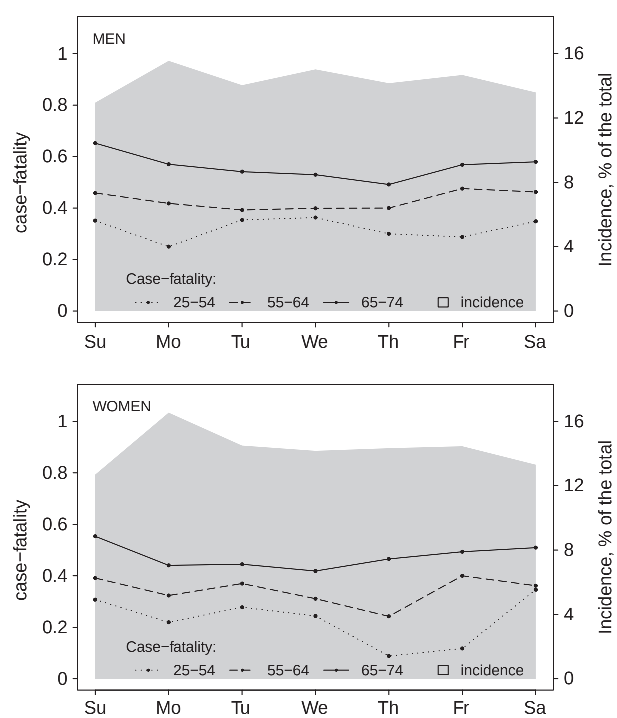

Figure 3. Weekly variation of first acute myocardial infarction (AMI) incidence and first AMI case fatality rates by age-group and sex for the years 1983, 1988, and 1993.

Table II. Coefficients and the mean squared errors (MSE) obtained from a 1-out cross-validation for the five different models of increasing complexity.

	No trend (NT)		Linear trend (LT)		Seasonal Fourier terms (FS)		Weather (W0)		W0+FS (WF)	
Model	Coefficient	*P*-value	Coefficient	*P*-value	Coefficient	*P*-value	Coefficient	*P*-value	Coefficient	*P*-value
Sex	−1.357	0.002	−1.358	0.002	−1.301	0.003	−1.348	0.002	−1.290	0.003
Age	0.043	<0.000	0.044	<0.000	0.044	<0.000	0.044	<0.000	0.044	<0.000
Sex × age	0.015	0.027	0.015	0.027	0.014	0.038	0.014	0.029	0.014	0.041
Temp [a]	–	–	–	–	–	–	−0.008	0.066	−0.001	0.930
Temp2 [b]	–	–	–	–	–	–	0.001	0.06	0.001	0.205
Time, t [c]	–	–	−0.002	0.710	–	–	–	–	–	–
SinWeek [d]	–	–	–	–	0.065	0.050	–	–	0.066	0.048
CosWeek [d]	–	–	–	–	0.141	<0.000	–	–	0.142	<0.000
MSE	0.2360		0.2360		0.2354		0.2362		0.2357	

[a] Temperature.
[b] Temperature squared.
[c] Change over time (linear trend).
[d] Fourier terms, functions of the day of the week.

Table III. Monthly case fatality rates of acute myocardial infarction in Finland 1983, 1988, and 1993 by sex and age.

	Men						Women					
Age	25–54 years		55–64 years		65–74 years		25–54 years		55–64 years		65–74 years	
Month	Deaths/cases	Rate	Deaths/cases	Rate	Deaths/cases	Rate	Deaths/cases	Rate	Deaths/cases	Rate	Deaths/cases	Rate
Jan	32/117	27%	54/139	39%	73/150	49%	7/23	30%	19/51	37%	68/147	46%
Feb	33/95	35%	63/136	46%	80/147	54%	2/19	11%	18/47	38%	65/127	51%
Mar	40/119	34%	73/150	49%	90/169	53%	3/22	14%	15/48	31%	58/147	39%
Apr	41/123	33%	66/143	46%	92/149	62%	7/25	28%	19/57	33%	61/145	42%
May	35/121	29%	41/124	33%	91/150	61%	3/19	16%	17/48	35%	58/120	48%
Jun	41/133	31%	65/156	42%	96/168	57%	8/24	33%	17/51	33%	59/112	53%
Jul	34/123	28%	67/137	49%	88/147	60%	1/14	7%	12/36	33%	74/136	54%
Aug	44/108	41%	69/157	44%	78/150	52%	2/19	11%	13/48	27%	57/137	42%
Sep	30/106	28%	54/132	41%	71/151	47%	5/22	23%	15/55	27%	56/128	44%
Oct	42/122	34%	52/124	42%	87/174	50%	3/18	17%	17/57	30%	67/131	51%
Nov	32/127	25%	48/127	38%	89/156	57%	5/21	24%	22/63	35%	59/141	42%
Dec	37/92	40%	57/128	45%	96/136	71%	7/12	58%	21/45	47%	75/127	59%

difficult to say whether higher mortality originates from a higher incidence of AMI or higher case fatality, or both. On the other hand the investigation of case fatality results in clearer policy implications in terms of ready availability of transport, medical personnel, and necessary treatment during the periods of expectedly high case fatality.

The AMI mortality has been declining steadily in the last decades. The reason for that is first and foremost the change in the incidence of AMI due to better primary and secondary prevention. However, the case fatality does not add much to this decline. One reason is that most of the deaths occur out of hospital, thus the improvement and wider availability of hospital treatment methods over time do not have an impact (31–33). This aligns with our results.

The highest case fatality of AMI in our study was in December. An earlier study focusing on seasonality of case fatality (22) also observed a higher level of case fatality in the winter months. Since data in that study included only in-hospital deaths the case fatality percentages were generally lower than found in our study.

The highest AMI case fatality occurred on Sundays. A previous study carried out in New Jersey, US, in 1987–2002 (34) found significantly higher mortality in patients admitted to the hospital during week-ends compared to those admitted on other weekdays. Patients were less likely to undergo invasive treatments, and the time between admission and performance of procedures was longer during week-ends than on weekdays. The reason for that might be the specialized hospital staffing, which is usually lower during week-ends than on weekdays. The same shortage relate to December holidays, where we found increased AMI case fatality as well.

Several studies have reported a significant Monday peak in AMI onset (35,36) and sudden death of presumably cardiac origin (37). The Monday incidence peak is also in evidence in our data. However, there is no reason for the incidence and case fatality to correlate unless high incidence becomes a cause of competition for resources (i.e. ambulances, hospital beds, medical staff, and medication), which is not the case in Finland.

Possible reasons for temporal or seasonal variation of case fatality of AMI may originate from several factors. One is the direct physiological impact of weather and season through e.g. temperature, air pollution, or pollen concentration (1,3,7,17,38–40). However, in our study we did not find a statistically significant effect of the temperature on the case fatality. Concomitant infectious diseases such influenza, pneumonia, or other respiratory infections also underlie seasonality and could add to the case fatality (22,41,42). Also blood pressure and peripheral vasoconstriction vary with the season (43,44). Although the incidence of infectious diseases, high blood pressure, and peripheral vasoconstriction are higher in the winter months, this cannot explain the peak in December. Time to treatment can also underlie seasonal fluctuations, e.g. extended time to reach the hospital in winter due to bad traffic conditions. However, these conditions are typically not extremely difficult in December. Kloner et al. (45) found a peak in coronary deaths during the Christmas holidays. They suggest a superimposing of respiratory infections, behavioural changes in the consumption of food, salt, and alcohol, and the emotional and psychological stresses of those holidays. Those reasons could be the same for the AMI case fatality peak during the December holidays found in this study, possibly with an additional factor of low specialized hospital staffing.

In conclusion, there is a statistically significant weekly and monthly variation in case fatality of AMI in Finland. The highest case fatality risk for AMI is during the Christmas season and on Sundays. Weather conditions were not found to have an effect on the case fatality.

Acknowledgements

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References

1. Gerber Y, Jacobsen SJ, Killian JM, Weston SA, Roger VL. Seasonality and daily weather conditions in relation to myocardial infarction and sudden cardiac death in Olmsted County, Minnesota, 1979 to 2002. J Am Coll Cardiol. 2006;48:287–92.
2. Kunst AE, Looman CW, Mackenbach JP. Outdoor air temperature and mortality in The Netherlands: a time-series analysis. Am J Epidemiol. 1993;137:331–41.
3. Goerre S, Egli C, Gerber S, Defila C, Minder C, Richner H, et al. Impact of weather and climate on the incidence of acute coronary syndromes. Int J Cardiol. 2007;118:36–40.
4. Ebi KL, Exuzides KA, Lau E, Kelsh M, Barnston A. Weather changes associated with hospitalizations for cardiovascular diseases and stroke in California, 1983–1998. Int J Biometeorol. 2004;49:48–58.
5. Braga AL, Zanobetti A, Schwartz J. The effect of weather on respiratory and cardiovascular deaths in 12 U.S. cities. Environ Health Perspect. 2002;110:859–63.
6. Basu R, Samet JM. An exposure assessment study of ambient heat exposure in an elderly population in Baltimore, Maryland. Environ Health Perspect. 2002;110:1219–24.
7. Morabito M, Modesti PA, Cecchi L, Crisci A, Orlandini S, Maracchi G, et al. Relationships between weather and myocardial infarction: a biometeorological approach. Int J Cardiol. 2005;105:288–93.
8. Huynen MM, Martens P, Schram D, Weijenberg MP, Kunst AE. The impact of heat waves and cold spells on mortality rates in the Dutch population. Environ Health Perspect. 2001;109:463–70.

9. Murray CJ, Lopez AD, Mathers CD, Stein C. The Global Burden of Disease 2000 project: aims, methods and data sources. Geneva: World Health Organization, 2001.
10. Murray CJ, Acharya AK. Understanding DALYs (disability-adjusted life years). J Health Econ. 1997;16:703–30.
11. Mathers CD, Loncar D. Projections of global mortality and burden of disease from 2002 to 2030. PLoS Med. 2006;3:e442.
12. Mokdad AH, Bowman BA, Ford ES, Vinicor F, Marks JS, Koplan JP. The continuing epidemics of obesity and diabetes in the United States. JAMA. 2001;286:1195–200.
13. Falkstedt D, Hemmingsson T, Rasmussen F, Lundberg I. Body mass index in late adolescence and its association with coronary heart disease and stroke in middle age among Swedish men. Int J Obes (Lond). 2007;31:777–83.
14. Barnett AG, Dobson AJ, McElduff P, Salomaa V, Kuulasmaa K, Sans S. Cold periods and coronary events: an analysis of populations worldwide. J Epidemiol Community Health. 2005;59:551–7.
15. Danet S, Richard F, Montaye M, Beauchant S, Lemaire B, Graux C, et al. Unhealthy effects of atmospheric temperature and pressure on the occurrence of myocardial infarction and coronary deaths. A 10-year survey: the Lille-World Health Organization MONICA project (Monitoring trends and determinants in cardiovascular disease). Circulation. 1999;100:E1–7.
16. Frost DB, Auliciems A, de Freitas C. Myocardial infarct death and temperature in Auckland, New Zealand. Int J Biometeorol. 1992;36:14–7.
17. Houck PD, Lethen JE, Riggs MW, Gantt DS, Dehmer GJ. Relation of atmospheric pressure changes and the occurrences of acute myocardial infarction and stroke. Am J Cardiol. 2005;96:45–51.
18. Crawford VL, McCann M, Stout RW, Changes in seasonal deaths from myocardial infarction. Q J Med. 2003;96:45–52.
19. Stewart S, McIntyre K, Capewell S, McMurray JJ. Heart failure in a cold climate. Seasonal variation in heart failure-related morbidity and mortality. J Am Coll Cardiol. 2002;39:760–6.
20. Dilaveris P, Synetos A, Giannopoulos G, Gialafos E, Pantazis A, Stefanadis C. CLimate Impacts on Myocardial infarction deaths in the Athens Territory: the CLIMATE study. Heart. 2006;92:1747–51.
21. Sheth T, Nair C, Muller J, Yusuf S. Increased winter mortality from acute myocardial infarction and stroke: the effect of age. J Am Coll Cardiol. 1999;33:1916–9.
22. Spencer FA, Goldberg RJ, Becker RC, Gore JM. Seasonal distribution of acute myocardial infarction in the second National Registry of Myocardial Infarction. J Am Coll Cardiol. 1998;31:1226–33.
23. Pajunen P, Koukkunen H, Ketonen M, Jerkkola T, Immonen-Raiha P, Karja-Koskenkari P, et al. The validity of the Finnish Hospital Discharge Register and Causes of Death Register data on coronary heart disease. Eur J Cardiovasc Prev Rehabil. 2005;12:132–7.
24. Mahonen M, Salomaa V, Brommels M, Molarius A, Miettinen H, Pyorala K, et al. The validity of hospital discharge register data on coronary heart disease in Finland. Eur J Epidemiol. 1997;13:403–15.
25. Uppala SM, Kallberg PW, Simmons AJ, Andrae U, da Costa Bechtold V, Fiorino M, et al. The ERA-40 re-analysis. Quart J Roy Meteor Soc. 2005;131:2961–3012.
26. ECWMF. ECMWF Data Server. Available from http: // data.ecmwf.int/data (accessed on 22.09.2008).
27. Karvonen M, Tuomilehto J, Virtala E, Pitkaniemi J, Reunanen A, Tuomilehto-Wolf E, et al. Seasonality in the clinical onset of insulin-dependent diabetes mellitus in Finnish children. Childhood Diabetes in Finland (DiMe) Study Group. Am J Epidemiol. 1996;143:167–76.
28. Hunsberger S, Albert PS, Follmann DA, Suh E. Parametric and semiparametric approaches to testing for seasonal trend in serial count data. Biostatistics. 2002;3:289–98.
29. Hastie T, Hastie T, Tibshirani R, Friedman JH. The Elements of Statistical Learning: Data Mining, Inference, and Prediction. New York: Springer, 2001.
30. R Development Core Team. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing; Vienna, Austria. 2005. Available from http: // www.R-project.org (accessed on 22.09.2008).
31. Salomaa V, Ketonen M, Koukkunen H, Immonen-Raiha P, Jerkkola T, Karja-Koskenkari P, et al. Trends in coronary events in Finland during 1983–1997. The FINAMI study. Eur Heart J. 2003;24:311–9.
32. Goldman L, Cook F, Hashimotso B, Stone P, Muller J, Loscalzo A. Evidence that hospital care for acute myocardial infarction has not contributed to the decline in coronary mortality between 1973–1974 and 1978–1979. Circulation. 1982;65:936–42.
33. Laatikainen T, Critchley J, Vartiainen E, Salomaa V, Ketonen M, Capewell S. Explaining the decline in coronary heart disease mortality in Finland between 1982 and 1997. Am J Epidemiol. 2005;162:764–73.
34. Kostis WJ, Demissie K, Marcella SW, Shao YH, Wilson AC, Moreyra AE. Weekend versus weekday admission and mortality from myocardial infarction. N Engl J Med. 2007;356:1099–109.
35. Gnecchi-Ruscone T, Piccaluga E, Guzzetti S, Contini M, Montano N, Nicolis E. Morning and Monday: critical periods for the onset of acute myocardial infarction. The GISSI 2 Study experience. Eur Heart J. 1994;15:882–7.
36. Willich SN, Lowel H, Lewis M, Hormann A, Arntz HR, Keil U. Weekly variation of acute myocardial infarction. Increased Monday risk in the working population. Circulation. 1994;90:87–93.
37. Arntz HR, Willich SN, Schreiber C, Bruggemann T, Stern R, Schultheiss HP. Diurnal, weekly and seasonal variation of sudden death. Population-based analysis of 24,061 consecutive cases. Eur Heart J. 2000;21:315–20.
38. Cold exposure and winter mortality from ischaemic heart disease, cerebrovascular disease, respiratory disease, and all causes in warm and cold regions of Europe. The Eurowinter Group. Lancet. 1997;349:1341–6.
39. Haber G, Witberg G, Danenberg H. [Air pollution and cardiovascular disease]. Harefuah. 2007;146:738–43, 816.
40. Ruidavets JB, Cournot M, Cassadou S, Giroux M, Meybeck M, Ferrieres J. Ozone air pollution is associated with acute myocardial infarction. Circulation. 2005 8;111:563–9.
41. Zambon MC. Epidemiology and pathogenesis of influenza. J Antimicrob Chemother. 1999;44(Suppl B):3–9.
42. Saynajakangas P, Keistinen T, Tuuponen T. Seasonal fluctuations in hospitalisation for pneumonia in Finland. Int J Circumpolar Health. 2001;60:34–40.
43. Woodhouse PR, Khaw KT, Plummer M. Seasonal variation of blood pressure and its relationship to ambient temperature in an elderly population. J Hypertens. 1993;11:1267–74.
44. Brennan PJ, Greenberg G, Miall WE, Thompson SG. Seasonal variation in arterial blood pressure. Br Med J (Clin Res Ed). 1982;285:919–23.
45. Kloner RA, Poole WK, Perritt RL. When throughout the year is coronary death most likely to occur? A 12-year population-based analysis of more than 220 000 cases. Circulation. 1999;100:1630–4.

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Epidemiology

Title: Seasonal variation of diagnosis of Type 1 diabetes mellitus in children worldwide.

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ABSTRACT

Aims: To determine if there is a worldwide seasonal pattern in the clinical onset of type 1 diabetes.

Methods: Analysis of the seasonality in diagnosis of type 1 diabetes was based on the incidence data in 0-14 year old children collected by the WHO DIAMOND project over the period 1990-1999. 105 centres from 53 countries worldwide provided enough data for the seasonality analysis. The incidence seasonality patterns were also determined for age- and sex-specific groups

Results: 42 out of 105 centres exhibited significant seasonality in the incidence of type 1 diabetes ($p<0.05$). The existence of significant seasonal patterns correlated with higher level of incidence and with the average yearly counts. The correlation disappeared after adjustment for latitude. 28 of those centres had peaks in October-January and 33 had troughs in June-August. Two out of the 4 centres with significant seasonality in the Southern hemisphere demonstrated a different pattern with peak in July-September and trough in January-March.

Conclusions: The seasonality of the incidence of type 1 diabetes mellitus in children under 15 years of age is a real phenomenon, as was reported previously and as is now demonstrated by this large standardized study. The seasonality pattern appears to be dependent on the geographical position at least as far as the northern/southern hemisphere dichotomy is concerned. However, more data are needed on the populations living below the 30th parallel north in order to complete the picture.

KEY WORDS: epidemiology, type 1 diabetes, children, environment

ABBREVIATIONS:

AIC – Akaike Information Criterion

SW – South Wales

INTRODUCTION

Type 1 diabetes mellitus results from a cellular-mediated autoimmune destruction of the β-cells of the pancreas. Autoimmune destruction of β-cells has multiple genetic predispositions and is also related to environmental factors that are still poorly defined (1). The incidence of type 1 diabetes has been increasing worldwide for decades at an average annual rate of 3% (2, 3).

Studies of diabetes seasonality usually distinguish between the seasonality of birth and seasonality of onset or diagnosis. Seasonality of birth implies the existence of seasonal environmental factors affecting development in utero (4), such as viral infections (e.g., mumps and congenital rubella) and the mother's intake of vitamin D (5). A recent study of 19 European regions did not find consistent evidence that seasonal environmental factors have any influence on the foetal or neonatal life to determine the onset of type 1 diabetes (6). Nevertheless, several other smaller studies have found some evidence for a pattern in the seasonality of birth, with a generally higher incidence for those born in spring and summer, than for those born in autumn and winter (4, 7, 8). In addition, with regard to the seasonality of birth, Laron et al (9) suggest that the pattern is only noticeable in ethnically homogenous groups.

The seasonality of onset or diagnosis of type 1 diabetes has also been extensively studied, and the results so far are conflicting. Although many studies have found evidence for seasonality (10-12), others have not (12, 13), and some studies only found seasonality in population subgroups (14, 15) . In general, older age groups and males seem to exhibit seasonality more often (14-16).

Viral infections and their immunological consequences are suspected to contribute to the pathogenesis of type 1 diabetes (17). While it has been reported that children with infection up to 3 months prior to diagnosis show a different seasonal pattern from children without infection (18), the link between the seasonal pattern of type 1 diabetes and viral infections has not been confirmed (19).

Within the existing body of research on seasonality there is a naturally large variability in data collection methods, the definition of study group (e.g., age of subjects), and the statistical methods employed in the analysis. In this study we use the data collected during the 10 years of the WHO Diabetes Mondiale Project (WHO DiaMond) with the registered active participation of over 100 centres worldwide and use the same statistical methodology throughout to investigate the seasonality of diagnosis of type 1 diabetes mellitus among 0-14 year olds. We have determined the statistical power of the applied test for the existence seasonality in order to assess the reliability of the results.

In this study we have examined these seasonal patterns both in sex-age subgroups and for the data pooled for each study centre. We have also compared the estimated patterns found at different latitudes. As a result, we have compiled a global pattern of seasonality of onset of type 1 diabetes, which, we believe, puts the local individual studies done so far into a global context and provides a springboard for further research into aetiological aspects of childhood type 1 diabetes.

PATIENTS AND METHODS:

Study Population. The detailed study plan and organizational structure of the WHO DiaMond incidence study have been described previously (20). The ten-year project, from 1990 to 1999, provided a consistent framework for the collection and analysis of the incidence data based on a well-defined population-based registry. For the study, every participating centre prepared its own local methods of operation which described the population base, the design of the registry, sources of data, data management, data items, and the time schedule of data collection in accordance with the framework provided by the WHO DiaMond incidence study.

The population at risk consisted of all the children under 15 years of age resident in the study area, which was defined geographically to correspond with administrative and census boundaries. The cases include all the children diagnosed with type 1 diabetes on the basis of the 1985 WHO classification of diabetes and diagnostic criteria (21) during 1990 to 1999, before their 15th birthday.

Participating centres have submitted annual incidence data to the WHO DiaMond data centre in Helsinki using standardized forms. Data on sex, ethnic group, date of birth, date of first insulin administration and data source are included in the database. Each data file analyzed in the data centre was sent back to the centres for final check up and data cleaning. Some centres provided complete coverage of the primary source; for the rest, the degree of ascertainment was estimated using the capture-recapture method. The resulting centre-specific rates were reported in (2) and were above 80% in most centres.

Statistical Analysis. In this analysis the data were subdivided into three age groups of 0-4, 5-9, and 10-14 years of age. For each centre c, age group a, sex s, and month m the monthly number of cases Y was assumed to follow Poisson distribution, adjusted for the population at risk N and the length of the month l.

$$Y_{c,s,a,m} \sim Pois(\mu_{c,s,a,m} N_{c,s,a} l_m) \qquad (1)$$

The Poisson distribution is a conventional choice when modelling incidence of a comparatively rare disease in a large population. The distribution mean was modelled using a log-linear regression with seasonal Fourier terms:

$$\log \mu_{c,s,a,m} = \alpha + \beta m + \sum_{k=1}^{K} \gamma_k^{(c)} \cos(\frac{2\pi km}{12}) + \gamma_k^{(s)} \sin(\frac{2\pi km}{12}) \quad , \qquad (2)$$

where *m* starts with 1 for January 1990 and goes up to 120 for December 1999. The number of terms, also called harmonics, *K*, lies between *0* (no seasonal terms) and *6* (each month has its own risk-level), and thus allows a variety of models with different degrees of smoothness. The optimal *K* was chosen by selecting a model with the smallest AIC (22) out of the *7* possible models (*K=0, …, 6*). Because not only the parameters of the regression (2) but also the number of parameters, *2K+2*, included in the model was estimated, the *p*-value for the test of statistical significance of the seasonal model vs. a non-seasonal one needed to be corrected as described in Hunsberger et al (23).

A pooled model was also run, where the age and sex of the study subjects was not taken into account.

For those centres, for which significant seasonality was detected (corrected $p<0.05$), seasonal patterns were estimated and peaks and troughs examined. Geographical coordinates were obtained for the centres and the dependence of binary presence/absence of seasonality on these modelled and tested by running a logistic regression model. The dependence of binary presence/absence of seasonality on the level of incidence was tested in a similar manner.

To assess the statistical power (i.e., probability of detecting seasonality when it exists) 1000 simulations were run for ‘slight’ seasonality of ±3% and strong seasonality of ±60% for the expected annual case counts ranging from 1 to 500 per year.

RESULTS:

105 centres from 53 countries had supplied sufficient data for at least one year, so that the seasonality could be examined. The detailed analysis of incidence trends in these centres has been performed earlier and presented in (2), therefore we do not repeat it here. The geographical situation of these centres is shown in Figure 1. Only 42 centres exhibited significant seasonality ($p<0.05$) in the incidence of type 1 diabetes when the data were pooled for age and sex. These are marked in Figure 1 by black dots, whereas those without significant seasonality are marked by grey dots. Of the centres which have exhibited significant seasonality 28 had peaks in winter months (October-January) and 33 had troughs in summer months (June-August). However, 2 out of 4 centres with significant pattern in the Southern hemisphere (Chile and Australia) demonstrated a different pattern with peak in July-September and trough in January-March. Figure 2 illustrates the result for Finland, the northernmost centre of the study, and for South Wales (SW), Australia – one of the four centres with statistically significant seasonality found from the Southern hemisphere. Although the patterns are not mirror images of each other, SW has generally higher incidence during the southern winter months and a trough in December and January. Finland, on the other hand, has a clear trough in June-July and peaks in early spring and late autumn.

Figure 3 illustrates seasonality patterns for all 42 centres found to exhibit statistically significant seasonality by the pooled model. The shades of grey reflect the difference in the percentage of annual incident cases, estimated to occur in each month, and the percentage expected under the completely uniform month distribution, i.e. 100%/12month = 8.33% per month. The darker shades correspond to relative peaks and the lighter ones to troughs. The centres are arranged by latitude in order to highlight the apparent difference between the patterns in the Northern vs. the Southern hemisphere.

The existence of significant seasonal pattern correlated with the higher level of incidence ($p=0.000259$) and with the average yearly counts ($p=0.000006$). The correlation disappeared when adjusted for the geographical location according to the latitude. Centres further away from the equator were on average more likely to exhibit seasonality ($p=0.000283$). The geographical location according to longitude, on the other hand, had no effect. When divided according to gender, Type 1 diabetes incidence for boys exhibited significant seasonality more often that that for girls (33 vs. 26 centres). When the data were further divided into three age groups, 0-4 years of age, 5-9 years of age, and 10-14 years of age, the incidence in older age groups, 5-14 years old, showed significant seasonality more often than that in the youngest age groups.

The simulations have shown that for slight seasonality, even the annual incidence of 500 cases will only result in the power of the test of 0*.2*. For large seasonal variation of ±60%, 10 incident cases are enough to obtain a power of at least 0.95.

DISCUSSION

The 105 centres included in the analysis submitted data on 31091 cases of type 1 diabetes diagnosed before 15 years of age, and the average annual population at risk comprised 40.5 million. This is the largest study of seasonality of diagnosis to date. The standardized data collection and quality control, as well as the uniform statistical methodology used to analyse all the data, permits easy comparison between centres, i.e., different geographical regions.

The results demonstrate the global pattern of seasonality and agree with the results of previous smaller studies. The winter peaks and summer troughs exist in many centres, both in the northern and the southern hemisphere.

Centres further from the equator were more likely to exhibit significant seasonality. Unfortunately, most of the data in this study came from the Northern hemisphere. The information from Asia and Africa is sparse and therefore this correlation is far from conclusive. The finding of significant seasonality correlated with the level of incidence. This is difficult to interpret, since due to the nature of the analysis, the probability of detecting an actual seasonality, the statistical power of the test, increases with the average number of cases per year. Therefore, seasonality may be found in populations with high incidence and thus, generally, high numbers of cases, because there is enough data to detect it. This might also explain why the seasonal pattern is most often found among older age groups and/or among boys, since the incidence of type 1 diabetes in these population subgroups is generally highest. On the other hand, both the high incidence and large seasonal variability may be triggered by a common, as yet unknown, factor.

Numerous reasons have been suggested for the apparent seasonality of onset or diagnosis of type 1 diabetes, such as seasonal variation in the levels of glycated haemoglobin and insulin (14). Seasonal viral infections are also suggested to play a role in the aetiology of type 1 diabetes, either by affecting the incidence level (24) or by changing the seasonal pattern itself (18). Douglas et al (14) suggested that diet and exercise may have an effect and that the computer game generation may play less videogames in the summer and exercise more. Another reason of similar nature may be the summer holidays, which provide a rest from school stresses and also more opportunities for exercising. Although this might explain the difference in the seasonality patterns between older and younger children, it fails to explain the difference between the sexes.

A recent study found a negative association between average daily ultraviolet B (UVB) radiation and the temporal incidence of type 1 diabetes (25), which suggests a possible explanation for the global pattern of summer and winter peaks, found here. We have assumed that the seasonal pattern remains stable from year to year, but a model where the regression coefficients γ of Equation 2 are time dependent is also possible. In order to provide statistically conclusive results such analysis would need longer time series than those available for most of the centres in the DiaMond data set. Nevertheless it provides an interesting avenue of further research.

In conclusion, the seasonality of the incidence of type 1 diabetes mellitus in children under 15 years of age is a real phenomenon, as was reported previously, and as is now demonstrated by this large standardized study. The seasonality pattern appears to be dependent on the geographical position at least as far as the northern/southern hemisphere dichotomy is concerned. However, more data are needed on the populations living below the 30th parallel north in order to complete the picture.

COMPETING INTERESTS

Nothing to declare

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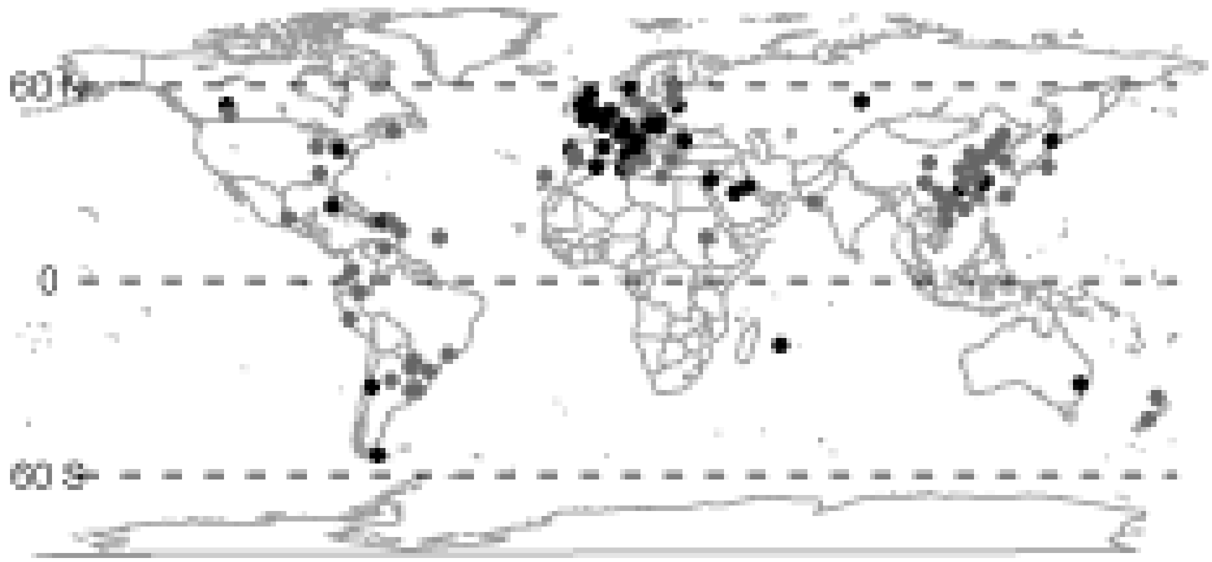
REFERENCES

1. Diagnosis and classification of diabetes mellitus. Diabetes Care. 2008 Jan;31 Suppl 1:S55-60.
2. Incidence and trends of childhood Type 1 diabetes worldwide 1990-1999. Diabet Med. 2006 Aug;23(8):857-66.
3. Onkamo P, Vaananen S, Karvonen M, Tuomilehto J. Worldwide increase in incidence of Type I diabetes--the analysis of the data on published incidence trends. Diabetologia. 1999 Dec;42(12):1395-403.
4. Rothwell PM, Staines A, Smail P, Wadsworth E, McKinney P. Seasonality of birth of patients with childhood diabetes in Britain. Bmj. 1996 Jun 8;312(7044):1456-7.
5. Vitamin D supplement in early childhood and risk for Type I (insulin-dependent) diabetes mellitus. The EURODIAB Substudy 2 Study Group. Diabetologia. 1999 Jan;42(1):51-4.
6. McKinney PA. Seasonality of birth in patients with childhood Type I diabetes in 19 European regions. Diabetologia. 2001 Oct;44 Suppl 3:B67-74.
7. Grover V, Lipton RB, Sclove SL. Seasonality of month of birth among African American children with diabetes mellitus in the city of Chicago. J Pediatr Endocrinol Metab. 2004 Mar;17(3):289-96.
8. Laron Z. Interplay between heredity and environment in the recent explosion of type 1 childhood diabetes mellitus. Am J Med Genet. 2002 May 30;115(1):4-7.
9. Laron Z, Lewy H, Wilderman I, Casu A, Willis J, Redondo MJ, et al. Seasonality of month of birth of children and adolescents with type 1 diabetes mellitus in homogenous and heterogeneous populations. Isr Med Assoc J. 2005 Jun;7(6):381-4.
10. Levy-Marchal C, Patterson C, Green A. Variation by age group and seasonality at diagnosis of childhood IDDM in Europe. The EURODIAB ACE Study Group. Diabetologia. 1995 Jul;38(7):823-30.
11. Willis JA, Scott RS, Darlow BA, Lewy H, Ashkenazi I, Laron Z. Seasonality of birth and onset of clinical disease in children and adolescents (0-19 years) with type 1 diabetes mellitus in Canterbury, New Zealand. J Pediatr Endocrinol Metab. 2002 May;15(5):645-7.
12. Padaiga Z, Tuomilehto J, Karvonen M, Dahlquist G, Podar T, Adojaan B, et al. Seasonal variation in the incidence of Type 1 diabetes mellitus during 1983 to 1992 in the countries around the Baltic Sea. Diabet Med. 1999 Sep;16(9):736-43.
13. Ye J, Chen RG, Ashkenazi I, Laron Z. Lack of seasonality in the month of onset of childhood IDDM (0.7-15 years) in Shanghai, China. J Pediatr Endocrinol Metab. 1998;11(3):461-4.
14. Douglas S, McSporran B, Smail P. Seasonality of presentation of type I diabetes mellitus in children. Scottish Study Group for the Care of Young Diabetics. Scott Med J. 1999 Apr;44(2):41-6.
15. Michalkova DM, Cernay J, Dankova A, Rusnak M, Fandakova K. Incidence and prevalence of childhood diabetes in Slovakia (1985-1992). Slovak Childhood Diabetes Epidemiology Study Group. Diabetes Care. 1995 Mar;18(3):315-20.
16. Mooney JA, Helms PJ, Jolliffe IT, Smail P. Seasonality of type 1 diabetes mellitus in children and its modification by weekends and holidays: retrospective observational study. Arch Dis Child. 2004 Oct;89(10):970-3.
17. Jaeckel E, Manns M, Von Herrath M. Viruses and diabetes. Ann N Y Acad Sci. 2002 Apr;958:7-25.

18. Samuelsson U, Carstensen J, Lofman O, Nordfeldt S. Seasonal variation in the diagnosis of type 1 diabetes in south-east Sweden. Diabetes Res Clin Pract. 2007 Apr;76(1):75-81.
19. Karvonen M, Jantti V, Muntoni S, Stabilini M, Stabilini L, Muntoni S, et al. Comparison of the seasonal pattern in the clinical onset of IDDM in Finland and Sardinia. Diabetes Care. 1998 Jul;21(7):1101-9.
20. WHO Multinational Project for Childhood Diabetes. WHO Diamond Project Group. Diabetes Care. 1990 Oct;13(10):1062-8.
21. Diabetes mellitus. Report of a WHO Study Group. World Health Organ Tech Rep Ser. 1985;727:1-113.
22. Hastie T, Tibshirani R, Friedman J. The elements of statistical learning; data mining, inference, and prediction.: Springer; 2001.
23. Hunsberger S, Albert PS, Follmann DA, Suh E. Parametric and semiparametric approaches to testing for seasonal trend in serial count data. Biostatistics. 2002 Jun;3(2):289-98.
24. Afoke A, Ludvigsson J, Hed J, Lindblom B. Raised IgG and IgM in "epidemic" IDDM suggest that infections are responsible for the seasonality of type I diabetes. Diabetes Res. 1991 Jan;16(1):11-7.
25. Sloka S, Grant M, Newhook LA. Time series analysis of ultraviolet B radiation and type 1 diabetes in Newfoundland. Pediatr Diabetes. 2008 Apr;9(2):81-6.



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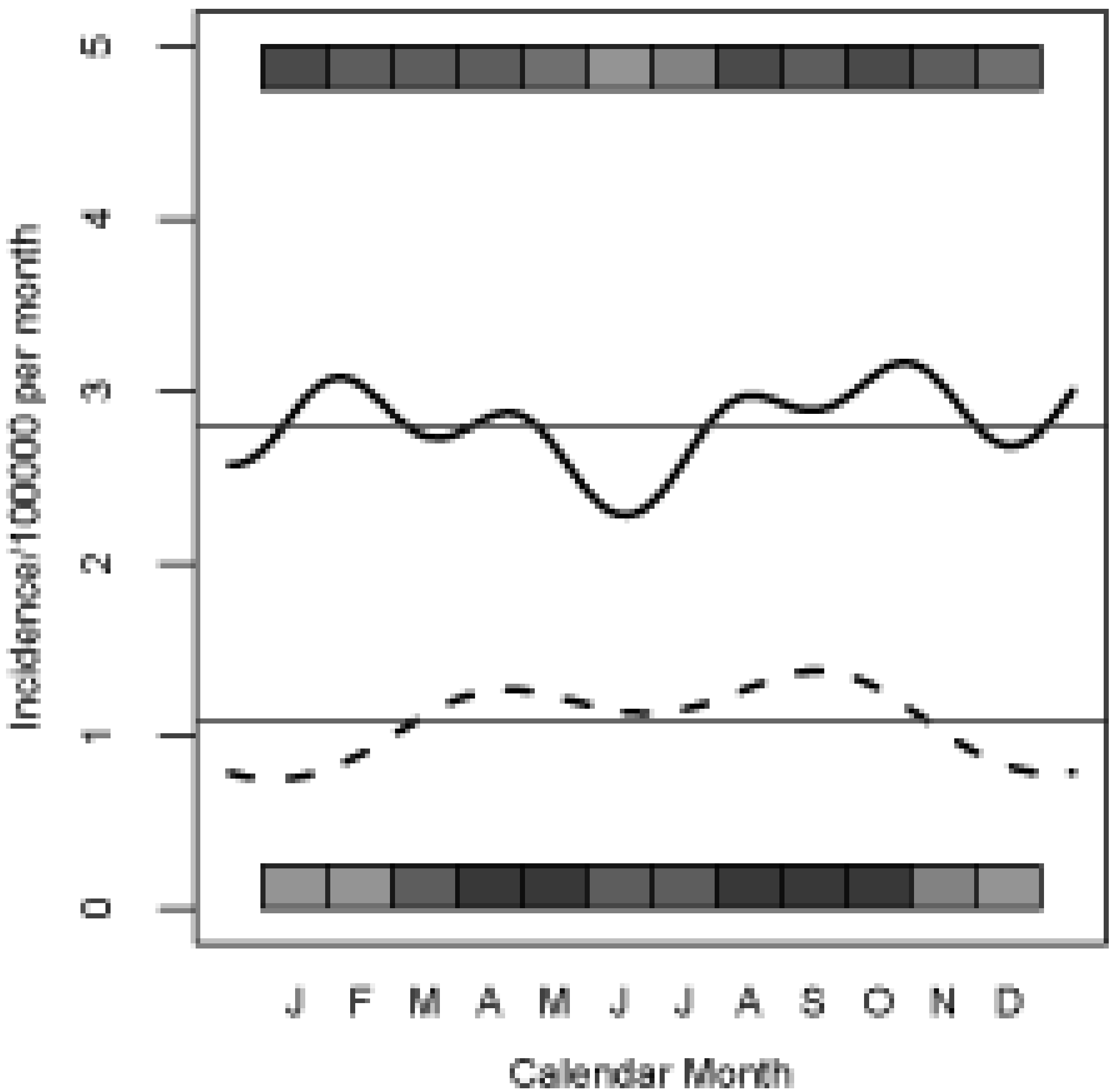

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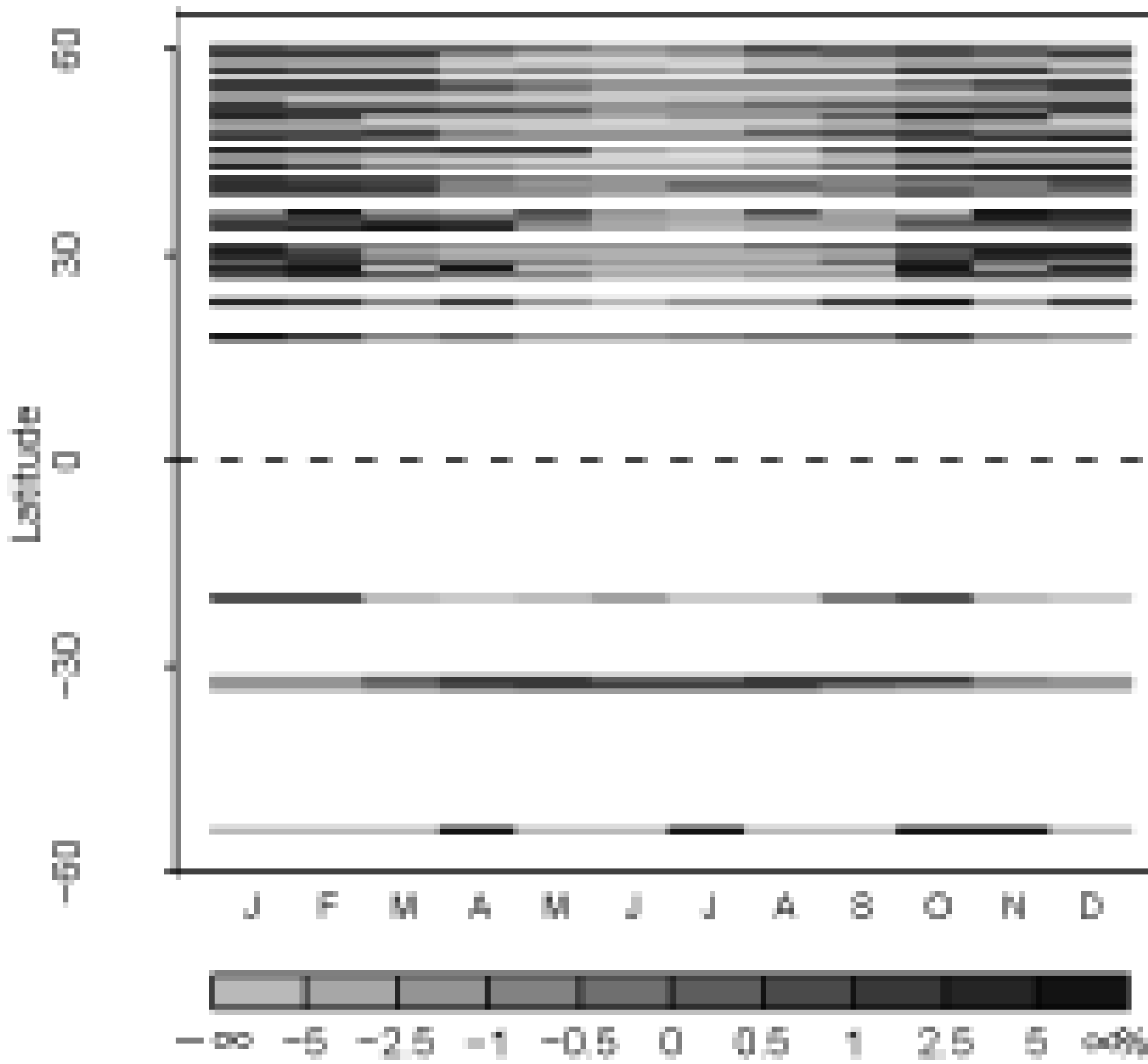
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A spatially explicit assessment of current and future hotspots of hunger in Sub-Saharan Africa in the context of global change

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ABSTRACT

Hunger knows no boundaries or borders. While much research has focused on undernutrition on a national scale, this report evaluates it at subnational levels for Sub-Saharan Africa (SSA) to pinpoint hotspots where the greatest challenges exist. Undernutrition is assessed with a spatial resolution of 30 arc-minutes by investigating anthropometric data on weight and length of individuals. The impact of climate change on production of six major crops (cassava, maize, wheat, sorghum, rice and millet) is analyzed with a GIS-based Environmental Policy Integrated Climate (GEPIC) model with the same spatial resolution. Future hotspots of hunger are projected in the context of the anticipated climate, social, economic, and bio-physical changes. The results show that some regions in northern and southwestern Nigeria, Sudan and Angola with a currently high number of people with undernutrition might be able to improve their food security situation mainly through increasing purchasing power. In the near future, regions located in Ethiopia, Uganda, Rwanda and Burundi, southwestern Niger, and Madagascar are likely to remain hotspots of food insecurity, while regions located in Tanzania, Mozambique and the Democratic Republic of Congo might face more serious undernutrition. It is likely that both the groups of regions will suffer from lower capacity of importing food as well as lower per capita calorie availability, while the latter group will probably have sharper reduction in per capita calorie availability. Special attention must be paid to the hotspot areas in order to meet the hunger alleviation goals in SSA.

1. Introduction

Food security means access at all times by all people to adequate amounts of safe, nutritious, and culturally appropriate food for an active and healthy life (World Bank, 1986). Our current times are regarded as more civilized than any periods before in human history, yet there are still a substantial number of people living in an insecure food situation. According to the Food and Agriculture Organization (FAO), in 2002–2004 approximately 864 million people (14% of the world population) were undernourished (FAO, 2006b). Hunger causes human suffering, enhances the rates of disease and mortality, limits neurological development, reduces labor productivity, and even holds back a nation's economic growth (UN Millennium Project, 2005). Particularly, for young children, the lack of food can be perilous, since it retards their physical and mental development and threatens their very survival. In 1996, the FAO World Food Summit set a goal of halving the proportion of people who suffer from hunger between 1990 and 2015. This goal was later incorporated into the United Nations' Millennium Development Goals (MDGs), and most countries committed to fight against lack of access to one of the most basic necessities — safe and adequate food resources.

Poverty and low food production are commonly regarded as two important factors leading to hunger (UN Millennium Project, 2005). As a whole, the world produces enough food for its entire population. Countries with a large number of hungry populations, such as India, also produce enough food to feed their entire population (Sanchez and Swaminathan, 2005). Despite the sufficient food supply, many poor people still cannot afford to purchase sufficient food on the market, leading to hunger problems (UN Millennium Project, 2005). Although the Green Revolution has brought higher food production in many parts of the world in the past three decades, the overall food production per capita is experiencing a decline in Africa (FAO, 2006a). Low food production associated with poverty remains the

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determining factor as to why starvation has occurred there (Sanchez and Swaminathan, 2005).

Two indicators are commonly used to monitor the progress of the MDGs to halve the world's hunger, as shown with indicators I and II (UN Millennium Project, 2005). Hunger indicator I gives the percentage of the human population below the minimum level of calorie intake (or dietary energy consumption). This indicator compares the actual calorie intake with the minimum amount of calorie needed for a normal and healthy life. Hunger indicator II provides information on the prevalence of children under five years of age who are underweight. By using these indicators on current levels of undernutrition, light can be shed on the geographical nature of poverty and hunger and how climate change and global economic uncertainties might impact future hunger situations.

Given the number of hungry people in the developing world and the increasingly complex risk to food security, policymakers are faced with an enormous challenge. Freeing people from hunger will require more and better-targeted investments, innovations, and policy actions, driven by a keen understanding of the dynamics, risks and forces that shape the factors affecting people's access to food and the links with nutrition (Von Braun et al., 2005). The national analysis of food security, as most commonly encountered in discussions of hunger and malnutrition in SSA, does not reflect the considerable variation in the food security condition of households within a particular country. Undertaking a spatially explicit assessment allows us to determine how much actual access individuals have to available food, and a closer insight can be gained into what actually might cause their food insecurity, what sort of actions might need to be taken, and where this action should be taken to reduce food insecurity. The importance of subnational studies has been recognized and a first attempt has been made to quantify hunger indicator II by the Task Force on Hunger in the UN Millennium Project (UN Millennium Project, 2005). The task force divides the world into 605 subnational units (provinces, states, districts), and identifies hunger hotspots where the prevalence of underweight children under the age of five is greater than or equal to 20%. Still, for hunger indicator I, insufficient attention has been paid to a spatially explicit assessment. So far, the most detailed measurement of hunger indicator I was provided by FAO. It takes into account food consumption per person and the extent of unequal access to food at a national level.

Climate is and certainly continues to be a factor that has an impact on food security, given the increased frequency of droughts and increasing temperature in the SSA region. Therefore, examining food production in the context of global change (climate change included) is critical in understanding the future situation of food security in SSA. Several studies have been conducted to investigate the possible impact of climate change on crop yields. However, the previous assessments have not identified the climate, socio-economic, and bio-physical changes which could drastically alter the overall food security situation and pose new challenges for future hunger reduction in SSA.

Scientific advances have made several high-resolution datasets available, e.g. current and future projected Gross Domestic Product (GDP) (Grübler et al., 2007) and population data (Grübler et al., 2007). These datasets are valuable to help conduct a spatially explicit assessment of the impact of global change on food security. In this paper, we first assess the current number of people suffering from undernutrition in SSA with a spatial resolution of 30 arc-minutes (about 50 km×50 km nearby the equator). Then, we analyze the impact of global climate change on food production in SSA with the same resolution. Finally, we investigate the future social (i.e., population), economic (i.e., GDP), and bio-physical (i.e., production) changes to identify potential hunger hotspots in order to locate those areas where the greatest challenges exist to fight against hunger in the future. Moreover, we investigate how these future potential hunger hotspots relate to the current undernutrition situation. SSA is selected as a case study, because it is a region with the highest hunger prevalence in the world, and the absolute numbers of hungry people are increasing (FAO, 2006b).

It should be pointed out that various terms are used to describe nutritional inadequacies, such as undernourishment, malnutrition, undernutrition etc., but there is no universally accepted terminology with an associated definition (see, e.g., FAO (1999) and WHO (1999)). According to FAO, undernourishment refers to the condition of people whose dietary energy consumption is continuously below a minimum dietary energy requirement for maintaining a healthy life and carrying out light physical activity. Undernutrition is used to indicate whether that people's food energy intake is insufficient or that the anthropometric scores of individuals are below selected cut-off points (Nube, 2001). Undernutrition is the result of undernourishment, poor absorption and/or poor biological use of the nutrients consumed. Malnutrition refers to a physical condition or process that results from the interaction of inadequate diet and infection and is most commonly reflected in poor infant growth; reduced cognitive development, anemia, and blindness in those suffering severe micronutrient deficiency; and excess morbidity and mortality in adults and children alike. Undernutrition, overnutrition and micronutrient deficiency are three forms of malnutrition (UNICEF, 1990). In this study, we use a method similar to that in Nube (2001) to assess the nutritional status in SSA and follow the term undernutrition. Since FAO uses the term undernourishment, we remain this original terminology of undernourishment when we present the results from FAO.

2. Method and data

2.1. Undernutrition

Undernutrition is estimated based on the anthropometric data on weight and length of individuals as reported by the Demographic and Health Surveys (DHS) (DHS, 2006). DHS are nationally representative household surveys that provide data for a wide range of monitoring and impact evaluation indicators in the areas of population, health, and nutrition. Standard DHS surveys have large sample sizes (usually between 5000 and 30,000 households) and are typically conducted every five years, to allow comparisons over time. In SSA, surveys are available for 37 of the 48 countries. For children, the surveyed data include: percentage of underweight children and severely underweight children 0–5 or 0–3 years of age. For women, the surveyed data include: weight, percentage with a Body Mass Index (BMI) below 18.5, and percentage with a BMI below 16 for seven age groups (15–19, 20–24, 25–29, 30–34, 35–39, 40–44, >45). In this paper, underweight children and adults with a BMI below 18.5 are defined as population with undernutrition. For children, the same indicator is used by the Task Force on Hunger in the UN Millennium Project, as stated above. For adults, the BMI value of 18.5 is often used as an indicator for nutritional status. For example, WHO (1995) used the cut-off point of 18.5 to classify the nutritional status of a population. If 10–19% of the population has a BMI lower than 18.5, the nutritional situation of the population is poor; 20–29% implies a seriously poor nutritional situation; while if over 40% of the population has a BMI lower than 18.5, immediate intervention must be taken to avoid starvation.

For countries and age groups where DHS data are available, the estimation of undernutrition is straightforward as both the percentage of underweighted children aged 0–5 and the percentage of women with BMI lower than 18.5 are reported. DHS surveys do not report on the prevalence of BMI for men. However, according to Nube and Van Den Boom (2003), there is no major difference of undernutrition between male and female adults in SSA. It can be therefore safely assumed that the nutritional status of women is representative for men in the same age groups. However, for children aged 5–9 we use the nutritional status of children aged five because the anthropometric data on underweight are rarely available for this age group. Similarly, we assume that the prevalence of undernutrition of the age group 10–14 is the same as that of women aged 15–19. It should be noted that there is still no universally accepted way to measure undernutrition status for the age group 10–14 (WHO, 2006). Whether to apply a BMI value or to use a reference weight to indicate the nutritional status for this age group is a topic of current debate.

The number of people suffering from undernutrition is first estimated at a district level. In this study, 3529 districts are included in SSA. Then, the number of undernourished people in each grid cell is estimated by assuming that the percentage of undernourished people remains the same for all grid cells within a district.

2.2. Impact of climate change on food production

In this study the impact of climate change on crop production is analyzed with the GEPIC model (Liu et al., 2007a,b). The GEPIC model is a bio-physical process-based model that simulates spatial and temporal dynamics of agricultural production and related processes such as weather, hydrology, nutrient cycling, tillage, plant environmental control and agronomics. GEPIC integrates an Environmental Policy Integrated Climate (EPIC, version 0509) model with a Geographical Information System (GIS) by a loose coupling approach. This approach connects the EPIC model with GIS through data exchange, and enables GEPIC to use all the functions of the EPIC model (Liu, in press).

GEPIC calculates daily potential biomass as a function of solar radiation, leaf area index (LAI), and a crop parameter for converting energy to biomass. The potential plant growth is driven by photosythentically active radiation. The amount of solar radiation captured by the crop is a function of LAI and the amount of solar radiation converted into plant biomass is a function of the crop-specific radiation use efficiency. The daily potential biomass is decreased by stresses caused by water shortage, temperature extremes, nutrient insufficiency and soil aeration inadequacy (Williams et al., 1989). The daily potential biomass is decreased in proportion to the severity of the most severe stress of the day. Crop yield is estimated by multiplying above-ground biomass at maturity by a water stress adjusted harvest index. The detailed description about the GEPIC model can be found in Liu et al. (2007b), Liu (in press) and Liu et al. (2008), while the detailed description of the EPIC model can be found in Williams et al. (1989).

The GEPIC model simulates the effects of temperature on crop yield mainly in two ways. First, the daily potential biomass is reduced by temperature stress, as mentioned earlier. Second, GEPIC uses heat unit to determine phenological development and duration of the growing season. The daily heat unit is calculated as the difference between daily mean temperature and a crop-specific base temperature. In addition, temperature is a determinant of soil evaporation and crop transpiration; hence, it affects the availability of soil moisture that sustains crop growth. The GEPIC model simulates the effects of precipitation on crop yield using a concept of water stress. When atmospheric demand for soil moisture exceeds soil moisture supply, a water stress day occurs and potential crop yield is reduced by a certain amount. In the GEPIC model, biomass energy conversion was affected by the level of CO_2 concentration using equations of Stockle et al. (1992), while the biomass conversion factor influences daily potential biomass growth.

Changes in temperature, precipitation and CO_2 concentration are the major variables used in this study to assess the effects of future changes on crop yield. All other factors influencing crop yield are assumed unchanged over time except for crop calendars. In the GEPIC model, an automatic calendar algorithm is developed. The model simulates crop yield considering all specified days as planting dates. The model compares crop yield simulated with all specified planting dates, and selects the highest yield. This algorithm theoretically involves an assumption that local farmers have perfect knowledge in selecting planting and harvest dates. When simulating the impact of climate change, this algorithm allows the farmers to adapt to climate change by adjusting the planting and harvest dates for optimized yield.

Six crops are selected for simulation: cassava, maize, wheat, sorghum, rice and millet. These crops are the most important crops in SSA (Lobell et al., 2008), and combined they account for over half the total calorie intake and over 60% of the calorie intake from vegetal food (FAO, 2006a). Only rainfed agriculture is simulated because it accounts for over 96% of total cereal harvest area and 93% of total cereal production in SSA (Rosegrant et al., 2002). In order to reduce the annual variations of crop yield, 10-year average yield is calculated for two periods: the 1990s (1990–1999) and the 2030s (2030–2039). We select the future period of 2030s mainly due to two reasons. First, this time period is most relevant to large agricultural investments, which typically take 15 to 30 years to realize full returns (Reilly and Schimmelpfennig, 2000). Second, a shorter period will lead to smaller changes in agricultural areas, adaptation, diet patterns, etc. The assessment is conducted with a spatial resolution of 30 arc-minutes because most spatially distributed data are available with this resolution.

The impact of climate change on food production of a certain crop is assessed by comparing the yields in the 2030s with those in the 1990s. Impact ratio (IR) of a crop is defined as the ratio of its yield in the 2030s to its yield in the 1990s. An IR value higher than one means crop yield will increase due to climate change, while an IR value lower than one means the crop yield will decrease. In this assessment, it is assumed that total crop area will not change and the crop types will not change in response to climate change and yield change. However it is expected that crop area is likely to further increase and crop types be adjusted to changes in climate in the future. Nevertheless, we intentionally leave both of these factors unchanged in order to assess the impact of climate change without agricultural area expansion and adaptation measures. The impact of climate change on total food production is assessed with the following equation:

$$IR = \frac{\sum_{c=1}^{6} Y_c^{2030s} \times A_c \times EC_c}{\sum_{c=1}^{6} Y_c^{1990s} \times A_c \times EC_c} \tag{1}$$

where IR is impact ratio, Y is crop yield in kg ha^{-1}, c is crop code, A is crop area in ha, and EC is energy content of a crop in kcal kg^{-1}. Data on EC are obtained from FAO (2006a) and the values of the six crops are reported in Liu and Savenije (2008).

Historical monthly data on maximum temperature, minimum temperature, precipitation and wet days between 1990 and 1999 were obtained with a spatial resolution of 30 arcminute from the Climate Research Unit of the University of East Anglia (CRU TS2.1) (Mitchell and Jones, 2005a). Since daily data are needed, a MOnthly to DAily WEather Converter (MODAWEC) model is used to generate the daily weather data (Liu et al., in press). The future monthly climate data on maximum temperature, minimum temperature, precipitation and wet days between 2030 and 2039 are obtained with the same resolution from the Tyndall Centre for Climate Change Research of the University of East Anglia (TYN SC 2.0) (Mitchell and Jones, 2005b). For the TYN SC 2.0 dataset, runs of the HadCM3 model (Gordon et al., 2000; Pope et al., 2000) for four scenarios are used: A1FI, A2, B1 and B2. The future daily climate data are generated with the MODAWEC model. The CO_2 concentrations in different scenarios are obtained from the ISAM model (reference) from the IPCC climate change report (IPCC, 2001).

Soil parameters of soil depth, percent sand and silt, bulk density, pH, and organic carbon content are obtained from Batjes (2006). Soil parameters are available for 5 soil layers (0–20, 20–40, 40–60, 60–80, 80–100 cm). All other data used for the GEPIC model have been described in detail in Liu et al. (2007b).

2.3. Population and GDP

The recent downscaled population and GDP data by the International Institute for Applied Systems Analysis (IIASA) (Grübler et al., 2007) are used in this paper. The IIASA datasets are produced with a 30 arc-minute resolution for the period 2000–2100. The projections of future population and GDP follow the qualitative scenario characteristics of the original SRES scenarios. We conduct a socio-economic analysis for different scenarios (A2r, B1 and B2), and we found that there is little difference between the different scenarios in terms of GDP and population development in the relatively short time span between the 1990s and the 2030s. In this paper, we only present the socio-economic analysis for the A2r scenario because this scenario tends to highlight potential future problems in Africa the most. The A2r scenario is a revised A2 scenario in order to reflect the recent reorganization that the A2 scenario may likely overestimate the future population (Grübler et al., 2007). The A2r scenario assumes a delayed fertility transition. The A2r scenario also assumes a delayed economic development. In this scenario the reduction in income disparities is initially stagnating, and then remains relatively slow.

The downscaling has been undertaken in two steps. In the first step, the results of population and GDP projections between 2000 and 2100 from the world regional scenarios (Grübler et al., 2007) are disaggregated to 185 countries. In the second step, the national data are further disaggregated to each grid cell with a spatial resolution of 30 arc-minutes by taking into account the income disparities between the rural and urban population. There are several advantages of using the IIASA's GDP and population datasets. First, the datasets are spatially explicit with a spatial resolution of 30 arc-minutes. Second, the data are scenario-dependent, and they are consistent with the original SRES scenarios. Third, structural changes such as urbanization rates are taken into account in different scenarios (Grübler et al., 2007).

2.4. Hotspot analysis of future food insecurity

We combine social, economic and bio-physical factors in order to assess the effects of global change on the future food security. Population as a social factor can influence total food demand. A higher population growth requires an increasing amount of food supply, and may impose threat to local food security. GDP on a per capita basis as an economic factor can influence the purchasing power. When local food production cannot meet the food demand of the population, a low GDP constrains the people from purchasing food from the market, and therefore results in food insecurity. Crop production as a bio-physical factor can directly influence the local food supply. In SSA, over 80% of cereal and almost all starchy roots were supplied by domestic production in 2000 (FAO, 2006a). Future food supply will have to heavily rely on domestic production when the purchasing power is not strong enough.

Agriculture is the primary source of livelihood for 65% of Africans, and 90% of African agriculture is small-scale (IFPRI, 2004). Hence, changes in crop yield due to climate change may affect most of the African population (IFPRI, 2004) in particular those in the regions where food insecurity exists and people rely on local agricultural production (Brown and Funk, 2008). Climate change may less impact on areas where there is a high degree of urbanization and people buy food on the market. Hence, we focus our analysis on areas where local food production accounts for the major share of the people's food consumption.

We first identified the grid cells with high reliance on food trade and the grid cells with high reliance on local food production. The grid cells with high reliance on food trade are mostly located in the places where urban population is high (e.g., over 1000 people/km^2 in this study). For those grid cells where population density is higher than 1000 people/km^2, it is assumed that all the food is supplied from outside. In low-density rural areas (i.e., $<$2.5 people/km^2 in this study), it is assumed that people there rely fully on locally produced food. Between these extremes a model has been developed (see SOW/WFP, forthcoming) which allocates the percentage of food imports for each grid cell, also taking into account areas which rely on food aid and areas with a high share of cash crops. We use a threshold of 50% to define those urban areas where subsistence agriculture plays a less important role. These areas are not considered in our analysis since food imports in those areas are substantial.

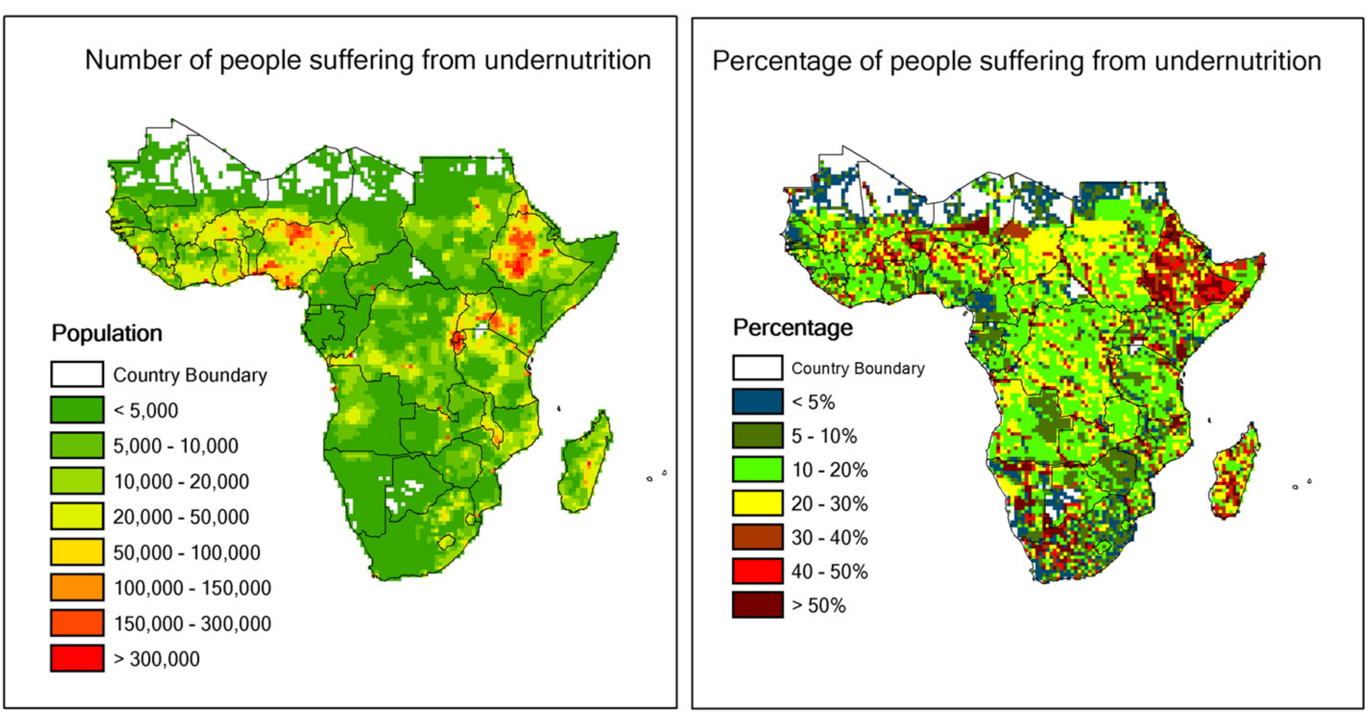

Fig. 1. Number and percentage of people suffering from undernutrition in SSA.

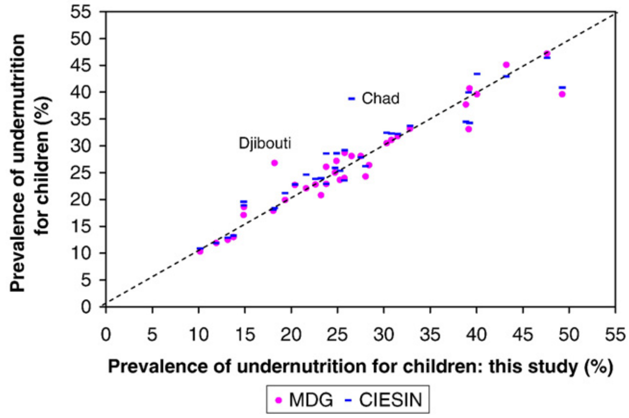

Fig. 2. Prevalence of undernutrition according to the share of young children under five who are underweight: a comparison among this study, MDG and CIESIN.

In order to understand whether the projected changes in yield will impact on the overall calorie availability in the future we calculate relative changes in per capita calorie availability between the 1990s and the 2030s. Moreover, we take into account the spatial distribution of the population density in the 2030s to understand where most people will be affected by this change in the areas of subsistence agriculture.

We undertake a separate analysis for the changes in per capita GDP. In order to determine whether a country or region is able to import more food in the future, we first calculate the overall global increase in per capita GDP between the 1990s and 2030s based on the IIASA scenario database (i.e. 3.6% in A2r scenario) (see Grübler et al. (2007). In case that the growth rate of per capita GDP in a grid cell is higher than the global average per capita growth rate between the 1990s and the 2030s, we assume that in this grid cell people will have more financial capacity to import food in the future than at present. In case that the growth rate of per capita GDP is lower than the global average growth rate we assume that less food per capita will be purchased in that grid cell.

We then combine the changes in per capita calorie availability with the projected future changes in per capita GDP. We select the areas of major concern with decreased per capita calorie availability as well as a slower growth rate of per capita GDP than the global average growth rate between the 1990s and the 2030s. Moreover, we select those areas with a minimum of two people per square kilometer to exclude the areas where little or no population lives.

In the last step, we examine the future hotspots through identifying the areas with current undernutrition problems, lower per capita calorie availability in the future, as well as a lower growth rate of per capita GDP than the global average in the future.

We acknowledge that the above approach to identify hotspots is somehow subjective. However, this study is the first attempt to combine socio-economic and bio-physical factors in order to assess the future hotspot of food insecurity; hence, we prefer to choose a transparent, simple and qualitative method here. A more sophisticated quantitative indicator (e.g. an index based approach) is not used because uncertainty is high in all the projections of the future factors.

3. Results

3.1. Current undernutrition situation in SSA

The spatial distribution of the number and percentage of people suffering from undernutrition is shown in Fig. 1. Grid cells with over 20,000 people suffering from undernutrition are mainly located in many Western African countries, several Eastern African countries (e.g., Ethiopia, Uganda, Rwanda and Burundi), and the eastern coastal area in Madagascar. The highest percentage of people with undernutrition is located in Eastern Africa (e.g. Ethiopia), Southern Africa (e.g., Namibia), and some Western countries (e.g. Niger, Burkina Faso). In SSA, approximately 120 million people (all age groups combined) had undernutrition problems in 2000 according to our calculation.

We compared the prevalence of undernutrition estimated in this study with those from other sources. First, both the United Nations' Millennium Development Goal (MDG) project and the Center for International Earth Science Information Network (CIESIN) at Columbia University provide the prevalence of undernourishment according to the share of young children under five who are underweight. MDG provides the data at the national level (http://mdgs.un.org), while CIESIN provides raster data with higher resolutions (e.g., 2.5′ resolution and 0.25° resolution) and shape file data at sub-country levels (http://www.ciesin.org). For comparison, we calculate the prevalence of undernutrition at the country level based on the high-resolution data from our study (i.e. 0.5° resolution) and CIESIN (i.e., 2.5′ resolution). Our results compare very well with those from both MDG and CIESIN in most countries (Fig. 2). Only some countries (e.g., Djibouti and Chad) have large differences. But for both Dijbouti and Chad, our results are close to those from at least one source of MDG and CIESIN.

Second, both the MDG database and FAO (2006b) provide the prevalence of undernourished people, and both sources share the same results. When comparing the results from these two sources with ours, we find that the total number of people suffering undernutrition estimated in this study is 39% lower than the total number of malnourished people from MDG and FAO. Particularly, our results show lower prevalence of undernutrition in Central, Eastern, and Southern Africa (Fig. 3). In agreement with our findings, several other studies have also argued that FAO overestimates the prevalence of undernutrition in SSA (Svedberg, 1999; Nube, 2001). For example, Nube (2001) estimates the prevalence of undernutrition in 13 countries in SSA, and calculates a prevalence of 5–18% in contrast to 14–48% according to FAO for adult women in SSA.

The different approaches to estimate the prevalence of undernutrition or undernourishment is the main reason for the above discrepancy. FAO estimates undernourishment based on its Food Balance Sheets. The sheets report food trade, production, and use by commodity at a national level. Food consumption is calculated as a residual item (consumption = production + imports − exports − feed use − seed use − industrial waste). The national average consumption is distributed over population to estimate per household availability of calories through income distribution information. With a cut-off point for per capita consumption, nutritional status is quantified at the household level. Total number of undernourished population in a country is estimated by aggregating the undernourished people in all households. For many years the FAO method of estimating undernourishment has been criticized as being unnecessarily complicated and sensitive to assumptions (Svedberg, 1999; Nube, 2001). Svedberg (1999) reveals that the FAO method is highly sensitive to relatively

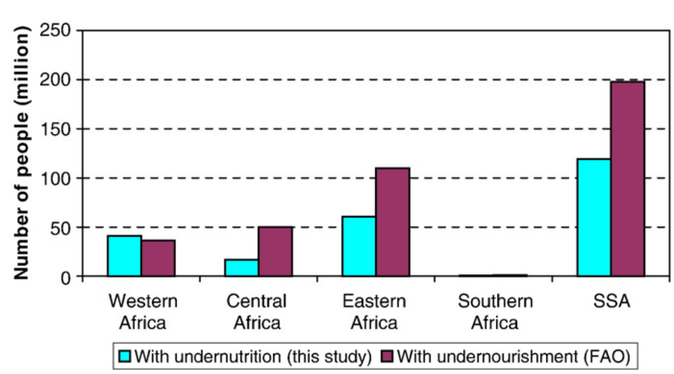

Fig. 3. Comparison of the number of people with undernutrition from this study and the number of malnourished people from FAO (2006b).

small "errors" in the exogenous parameters. For the FAO method, by adjusting the calorie availability by plus/minus 10%, distribution parameter by plus/minus 0.05 and calorie cut-off point by plus/minus 10%, the prevalence of undernourishment in SSA can be ranged from 21% to 61% in 1990–92 (Svedberg, 1999). The ranges of the three parameters are all very possible considering the large uncertainty of their estimation from FAO. The prevalence of undernourishment is wide enough to challenge the accuracy of the estimation by FAO. In contrast, anthropometric measurements are more reliable and relevant for all purposes for which indicators of undernutrition are needed (Svedberg, 1999). There are several advantages of the anthropometrics method, e.g. representativeness of the anthropometric data for individuals, simplicity, accuracy and low estimation costs, etc. Although confronting many critics, FAO still remains the most widely used source of information for the number of hungry people. The reasons are multi-folded, and include the fact that FAO was the first organization conducting the relevant study, and that FAO is a leading and influential organization for global food studies. Nevertheless, comprehensive estimation of the prevalence of undernutrition must be done to direct reasonable food policies in light of the large discrepancy of results from different sources. Therefore, efforts are urgently required in order to bring together the world experts to discuss the best approach to estimate the prevalence of undernutrition and to find consensus, as well as best practice guidelines.

3.2. Impact of climate change on crop production

In this paper, we assess the impact of climate change on crop production by considering the simultaneous change in CO_2 concentration. Climate change and change in CO_2 concentration are two closely related processes. Climate change is, to a large extent, a result of the increasing amount of CO_2 emissions to the atmosphere. Hence, they should be considered together when conducting an impact assessment.

Figs. 4–7 present the impact ratio of climate change (including the CO_2 change, we use "climate change" in this paper) on crop yield for six crops in four scenarios. The results show that all climate scenarios lead to very similar patterns of yield change. This is because, in the 2030s, there is little difference among the four climate scenarios. According to our results, the yield of wheat will be dominantly reduced across SSA in the 2030s compared to the 1990s, which is indicated by the impact ratio being generally lower than one in all scenarios (Figs. 4–7). The optimal temperature of wheat is generally between 15–20 °C, depending on the varieties of wheat (e.g., winter or spring wheat). The annual average temperature across SSA is already above this optimal temperature in the 1990s during the crop growing period. Due to global warming, temperatures will further increase until the 2030s, leading to reduction of crop yield of wheat. In contrast, millet will benefit from climate change in almost the entire

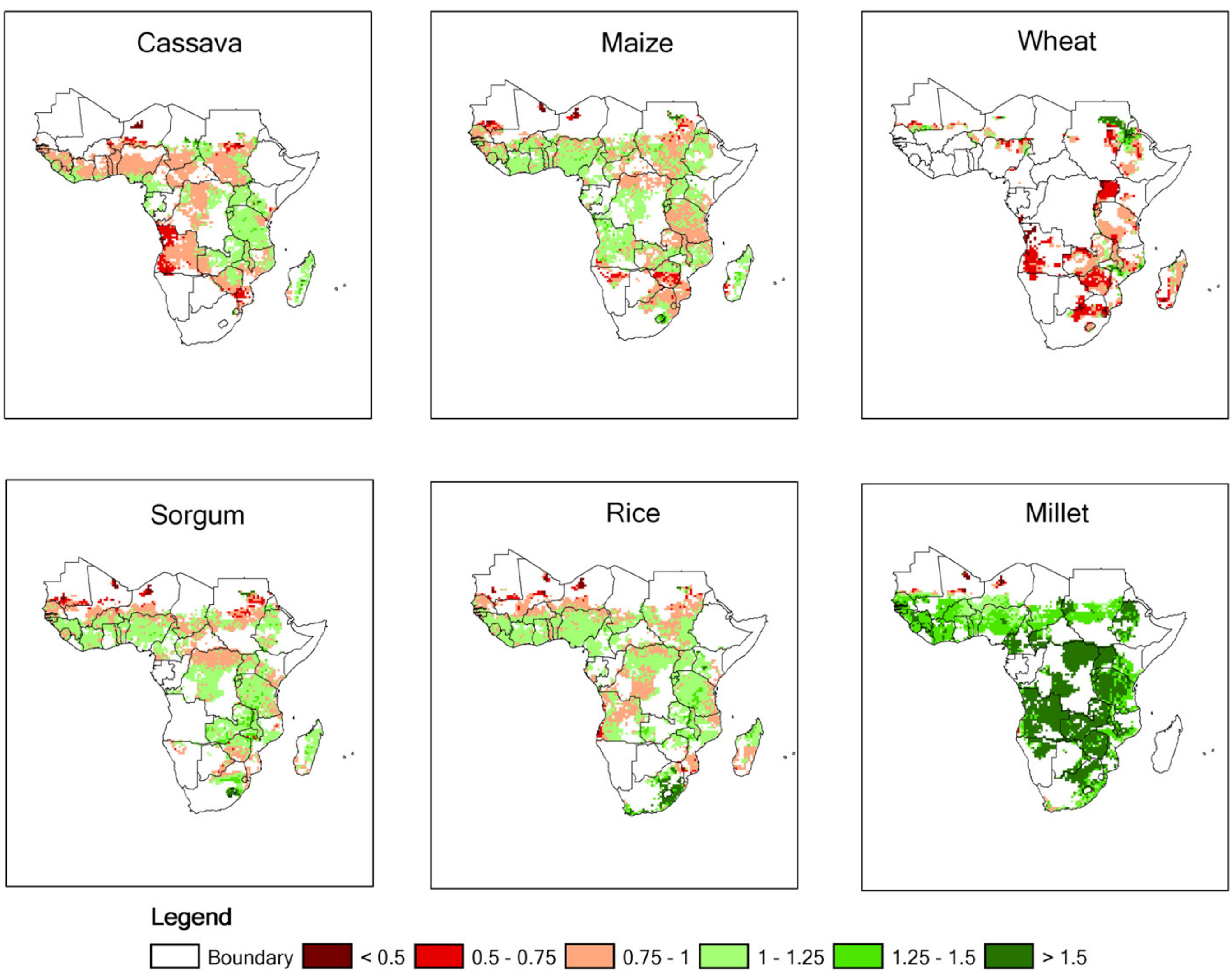

Fig. 4. Impact ratio of climate change on crop yield in Africa (A1FI scenario).

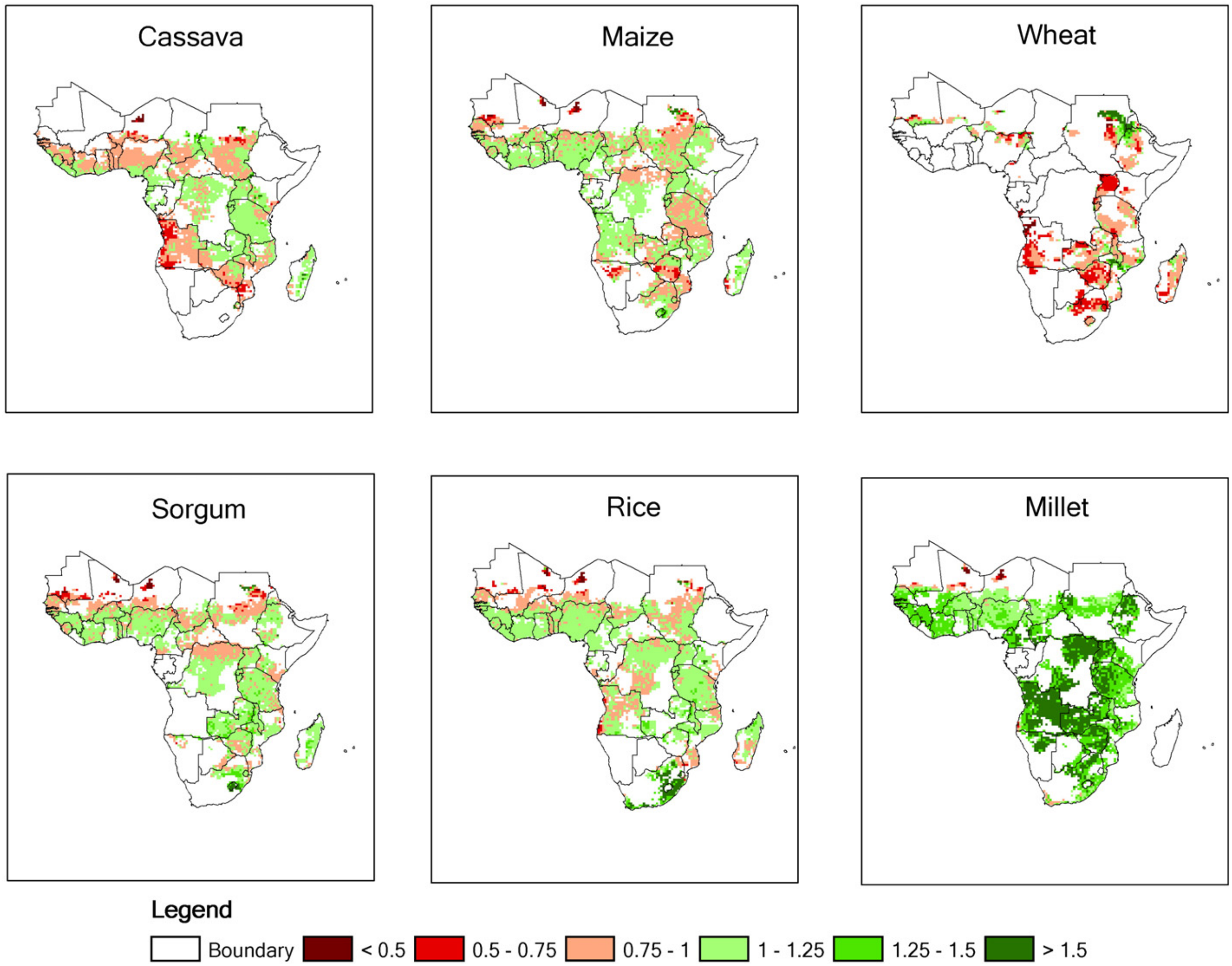

Fig. 5. Impact ratio of climate change on crop yield in Africa (A2 scenario).

SSA. Millet has an optimal temperature of around 30 °C. Climate change will result in temperature close to this optimum across SSA; as a result, crop yield of millet increases. Both cassava and sorghum have an optimal temperature of 27.5 °C. The impact ratios of both crops show similar spatial patterns, e.g. lower than one in most of the semiarid area along the Sahel desert and southern part of Zimbabwe and higher than one in large parts of Eastern Africa. Both maize and rice have an optimal temperature of 25 °C. The yield of both crops will be reduced along the Sahel desert. In other regions, rice may benefit more from global climate change than maize. As a C3 crop, rice can benefit more in terms of crop yield from the increased CO_2 concentration than maize (a C4 crop). This can partly explain the different responses of rice and maize to future climate change.

According to our estimate, for SSA as a whole, climate change will lead to 16–18% lower yield for wheat, 7–27% higher yield for millet, 5–7% higher yield for rice, and 3–4% higher yield for maize, depending on different scenarios (Fig. 8). For sorghum and cassava, changes in crop yield are very small. For six crops as a whole, climate change will lead to a slight increase of crop yield by 1.6–3.3% (Fig. 8). The changes in crop yield are well explained by the change in temperature, although other climatic factors also play roles. For example, the annual average temperature in the 1990s was 20.34 °C in wheat harvest area in SSA. This temperature is slightly higher than the optimal temperatures of most wheat varieties. In the future, climate change will lead to higher temperatures, which are even further away from the optimal temperatures of wheat. Partly due to this, crop yield of wheat will decrease. Another example, in the harvest area of millet, the annual average temperature was 27.27 °C in the 1990s, lower than the optimal temperature of millet. Climate change will lead to temperatures ranging from 28.30 °C to 28.54 °C in the 2030s depending on different scenarios. These temperatures are closer to the optimal temperature of millet; as a result, there will be a general increase in the crop yield of millet in SSA.

To assess the impact of climate change on the production of all studied crops as a whole, we sum up the available calories from local crop production in the 1990s and 2030s, and calculate the impact ratio values (see Eq. (1)), or the ratio of total calories in the 2030s to that in the 1990s. The results are shown in Fig. 9 for A1FI, A2, B1 and B2 scenarios. The national average impact ratios are indicated in Fig. 10 for the four scenarios. In seven countries, climate change will result in a reduction in crop yield in all scenarios. These include Mauritania, Congo, Gabon, Botswana, Swaziland, Zimbabwe, and Angola. Adaptation and mitigation measures should be taken soon to combat the adverse effect of climate change on crop production. In contrast, in 23 countries, climate change will lead to higher crop yield in all scenarios. These countries include Lesotho, Madagascar, Eritrea, Togo, Ivory Coast, Equatorial Guinea, Nigeria, Burundi, Burkina Faso, Benin, Uganda, Ghana, South Africa, Liberia, Ethiopia, Guinea-Bissau,

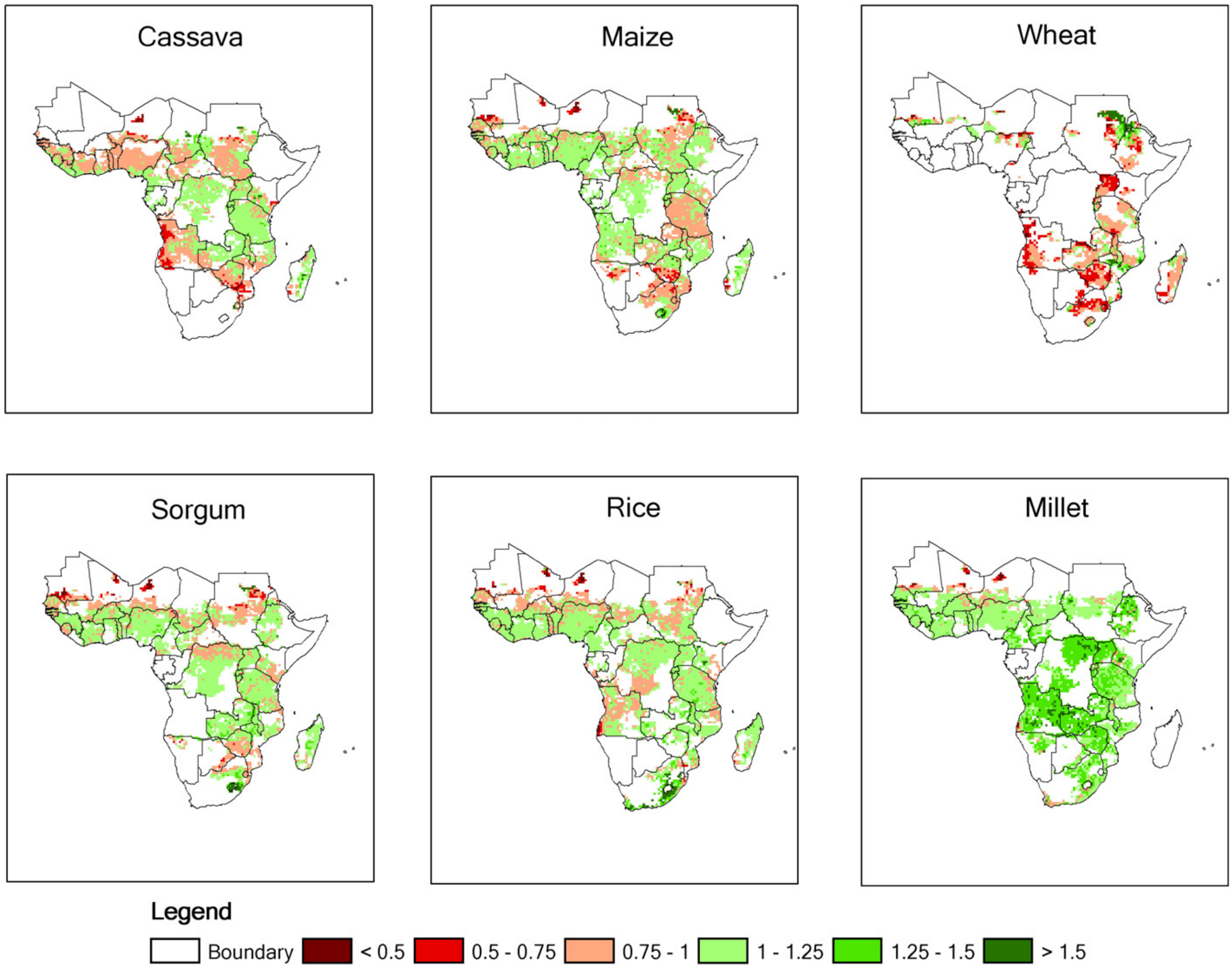

Fig. 6. Impact ratio of climate change on crop yield in Africa (B1 scenario).

Rwanda, Guinea, Sierra Leone, Kenya, Malawi, Senegal, and Gambia. In other countries, crop yield may increase or decrease depending on different scenarios.

Our study reveals a slightly positive change in crop yield for six crops as a whole in SSA. While wheat has a sharp decrease in crop yield, for all other crops, the yield will be much higher (e.g., for millet), slightly higher (e.g., for maize and rice), or remain almost unchanged (e.g., for cassava and sorghum). The general conclusion from this study – or a slightly higher yield in SSA in the 2030s compared to the 1990s – agrees well with some studies (e.g. Adejuwon (2006)) which predict an increase in crop yield in the first half of the 21st century, while it contradicts several others that indicate a decrease in crop production in Africa (Parry et al., 1999, 2004; Reilly and Schimmelpfennig, 1999; Jones and Thornton, 2003). Here, two issues need to be pointed out. First, this study assesses the impact of climate change for each grid cell. The assessment considers the different climatic conditions in all the grid cells. Many previous studies mainly focus on some specific sites, and interpolate the results to a large area (e.g. Rosenzweig and Parry (1994), Adejuwon (2006)); or they assess the impact for different countries or regions as a whole without considering the local variations (e.g. Parry et al. (2004)). Second, a number of previous studies often ignore the change in CO_2 concentration; hence, the "fertilization" of CO_2 is not taken into account, likely leading to an underestimation of crop yield in the future.

Direct comparison of the impact of climate change on crop production between this study and other studies is difficult because they encompass a range of different periods, regions and crops, and the uncertainty ranges can come from several sources such as spatial variability in yield, uncertainty in climate information, and different crop simulation methods (Challinor et al., 2007). We compare our results with the most recent studies. Lobell et al. (2008) project the potential yield change in 2030 with statistical crop models and climate projections from 20 general circulation models. There are several similar findings reported in Lobell et al. (2008) and the current study. First, both studies suggest that maize and wheat in Southern Africa will have lower yields in the 2030s. Second, the yield of cassava will generally not be highly affected by climate change. Third, rice will have a higher yield in Eastern and Southern Africa, and lower yield in Central Africa. Despite these similar findings, discrepancy exists between the two studies. For example, Lobell et al. (2008) found a high probability of lower maize yield in SSA in the future, while this study indicates slightly higher maize yield. The reason for the difference may be partly due to the fact that Lobell et al. (2008) ignored the effect of the change of CO_2 concentration, which leads to a somehow underestimation of crop yield in the future. When not considering the change of CO_2 concentration, the GEPIC model also shows a lower yield of maize, e.g. in the A1FI scenario (data are not shown here). Parry et al. (2004) estimate the current and future yield at a national level using yield transfer functions. They conclude that

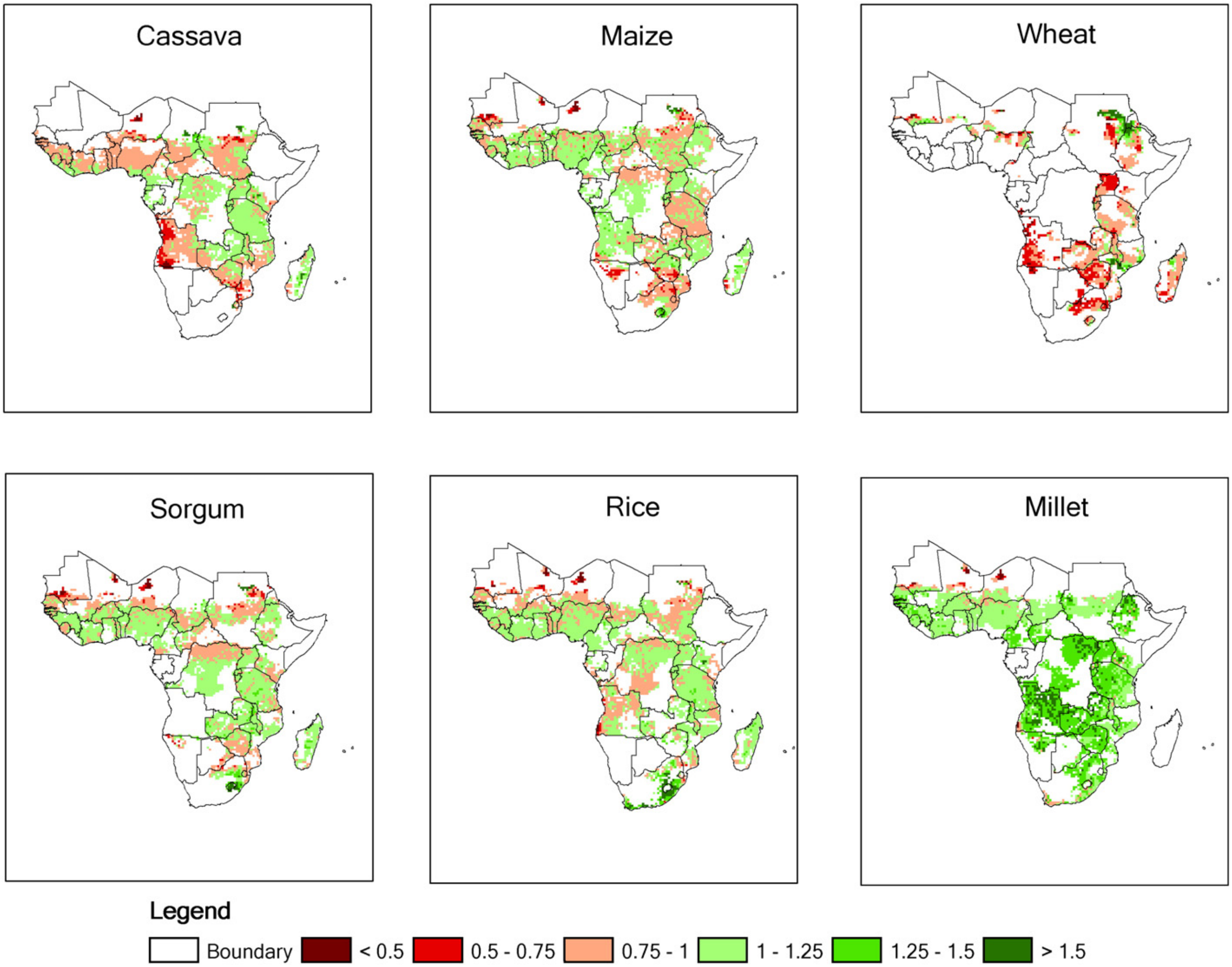

Fig. 7. Impact ratio of climate change on crop yield in Africa (B2 scenario).

total crop yield in Africa may decrease up to 30% in the 2080s compared to 1990. Parry et al. (2004) assess crop yield change for wheat, maize, rice, and soybean, but they do not estimate the change for cassava, sorghum and millet. However, the latter three crops are very important for calorie intake in Africa. Particularly for millet, crop yield may greatly increase in the future according to our calculation. Besides the different studied periods, the selection of different crops is a major reason for the difference in the yield change between this study and Parry et al. (2004).

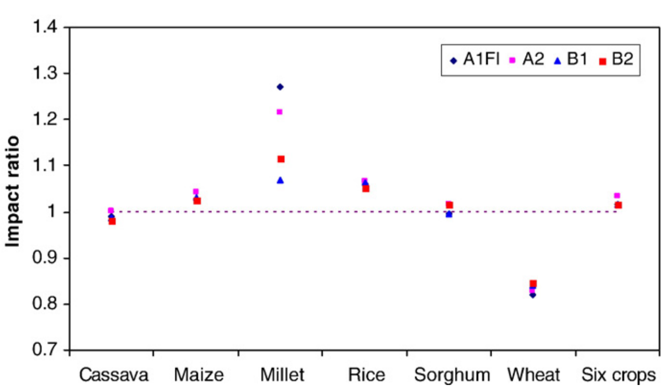

Fig. 8. Impact ratio of climate change for six crops in SSA (with physiological CO_2 effect).

Jones and Thornton (2003) use a CERES-Maize model and climate output of a global circulation model, and estimate an overall reduction of 15% in maize production in SSA by 2055. This conclusion contradicts our findings. Besides the difference in the studied periods, two major reasons explain the contradiction. First, Jones and Thornton (2003) do not take into account the "fertilization" effect of CO_2 in the atmosphere. Second, the different models used (i.e. GEPIC in this study versus CERES-Maize in Jones and Thornton's) may be another important reason for the difference, although a comparison of the models is beyond the scope of this paper.

3.3. Change in per capita calorie availability between the 1990s and the 2030s

As we have demonstrated in the last section climate change is likely to affect Africa differently at different locations. Even though the overall yields will not decrease according to this study, per capita calorie availability may decrease when considering population growth. We calculate the change in per capita calorie availability between the 1990s and the 2030s (see Fig. 11). Grid cells with an increase in per capita calorie availability are displayed in blue tones. A substantial increase in per capita calorie availability can only be found in many parts in South Africa, Zimbabwe, Botswana and Mozambique. Noticeable increase can also be found in a confined

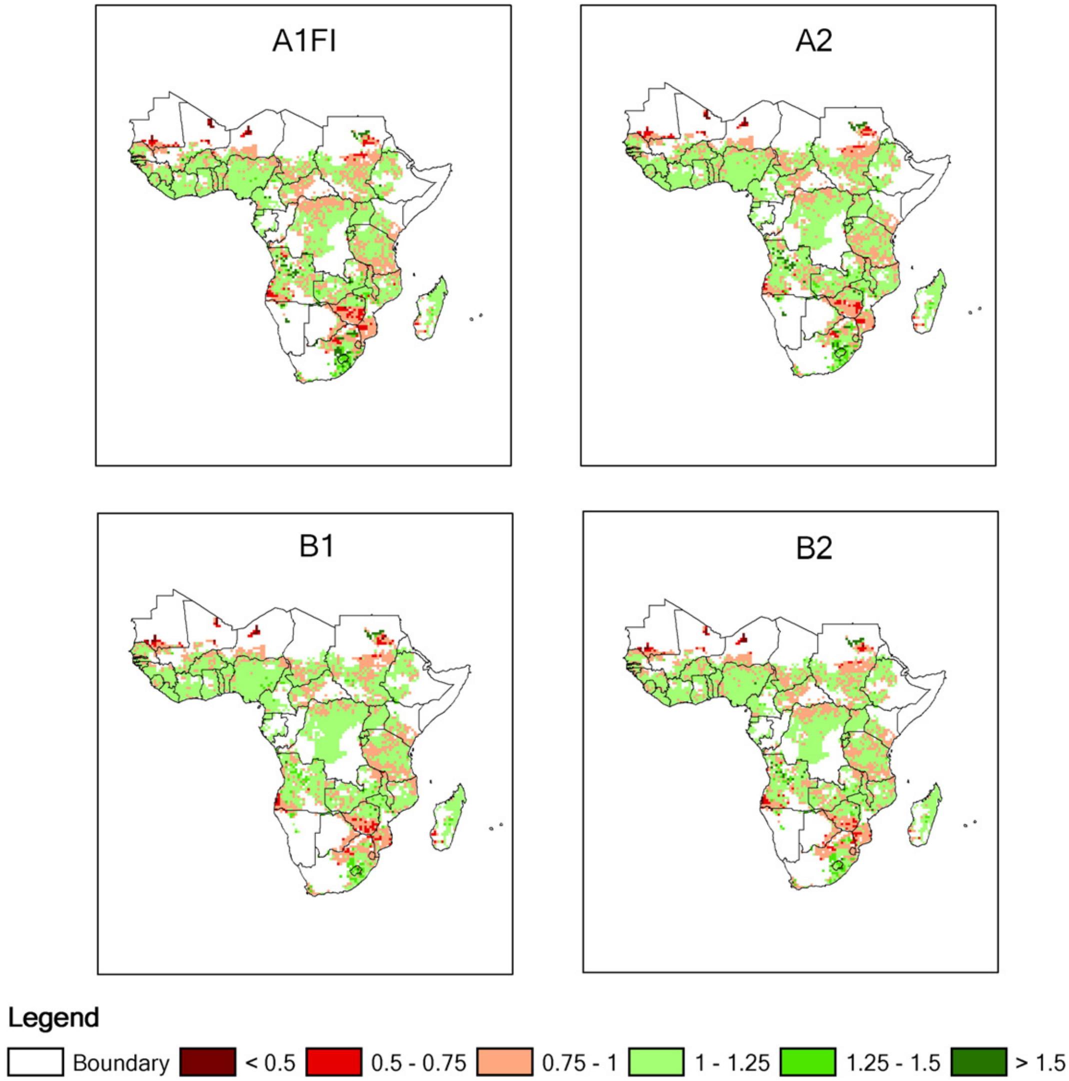

Fig. 9. Impact ratio of climate change on crop production in Sub-Saharan Africa for A1FI, A2, B1 and B2 scenarios.

border region of Chad, Niger and Nigeria. Grid cells with decreased per capita calorie availability between the 1990s and the 2030s are shown in red, orange, yellow and green tones. In order to visualise the distribution of the population in the same map, we show the higher population density with an increasing strength of red, orange, yellow, green and blue tones. Areas with a high degree of urbanization are displayed in a separate layer with the colour black, while the areas currently relying mainly on subsistence agriculture are shown with other colours on the maps. Areas with strong red and brown tones are of major concern. These areas are likely to face very serious undernutrition problems. Population there relies to a high degree on subsistence agriculture. These areas are located in Guinea, Ivory Coast, Sierra Leone, Liberia, Niger, Nigeria, Chad, Northern Sudan, Ethiopia, Angola, Kenya, Uganda, Democratic Republic of Congo, Uganda, Madagascar, and northern Tanzania.

3.4. Change in per capita GDP between the 1990s and the 2030s with respect to population

It can be argued that the hotspots located in Fig. 11 may change when there will be a substantial increase in purchasing power in the 2030s. We therefore undertake a separate analysis looking at potential future changes in the capacity to import food. By calculating the growth rate of GDP per grid cell with respect to the global average growth rate between the 1990s and 2030s (see the method described in Section 2.4), we find that many areas in Africa are not likely to import more food on a per capita basis in the future. In order to indicate the locations where most of the people will be living we add population density numbers for 2030s to Fig. 12. Particularly the areas located in southern Mali, Burkina Faso, Mozambique, Tanzania, Uganda, Somalia, and Madagascar are likely to experience a dramatic decrease in the capacity to import food on a per capita basis than currently (see Fig. 12). These regions have the lowest growth rate of GDP in SSA. Other areas located in south-western Ivory Coast, Ethiopia, southern Uganda, and Angola might also experience a lower capacity of being able to import food (see Fig. 12) as the growth rates of GDP in these areas are 30–60% lower than the world average growth rate between the 1990s and the 2030s. Areas with a high population density in the 2030s and the highest growth rate of GDP between the 1990s and the 2030s are located in Sudan, southern Kenya and Central Zambia (see Fig. 12). Other population-dense areas such as western Guinea, a large part of Ghana, Togo, Benin, Nigeria, western part of Central Africa, Zambia, Zimbabwe, northern part of Kenya, and some places in the Democratic Republic of Congo also have a projected increase in the capacity of being able to import food in the future. The effect of the increasing purchasing power may compensate the decrease in per capita calorie availability in these areas.

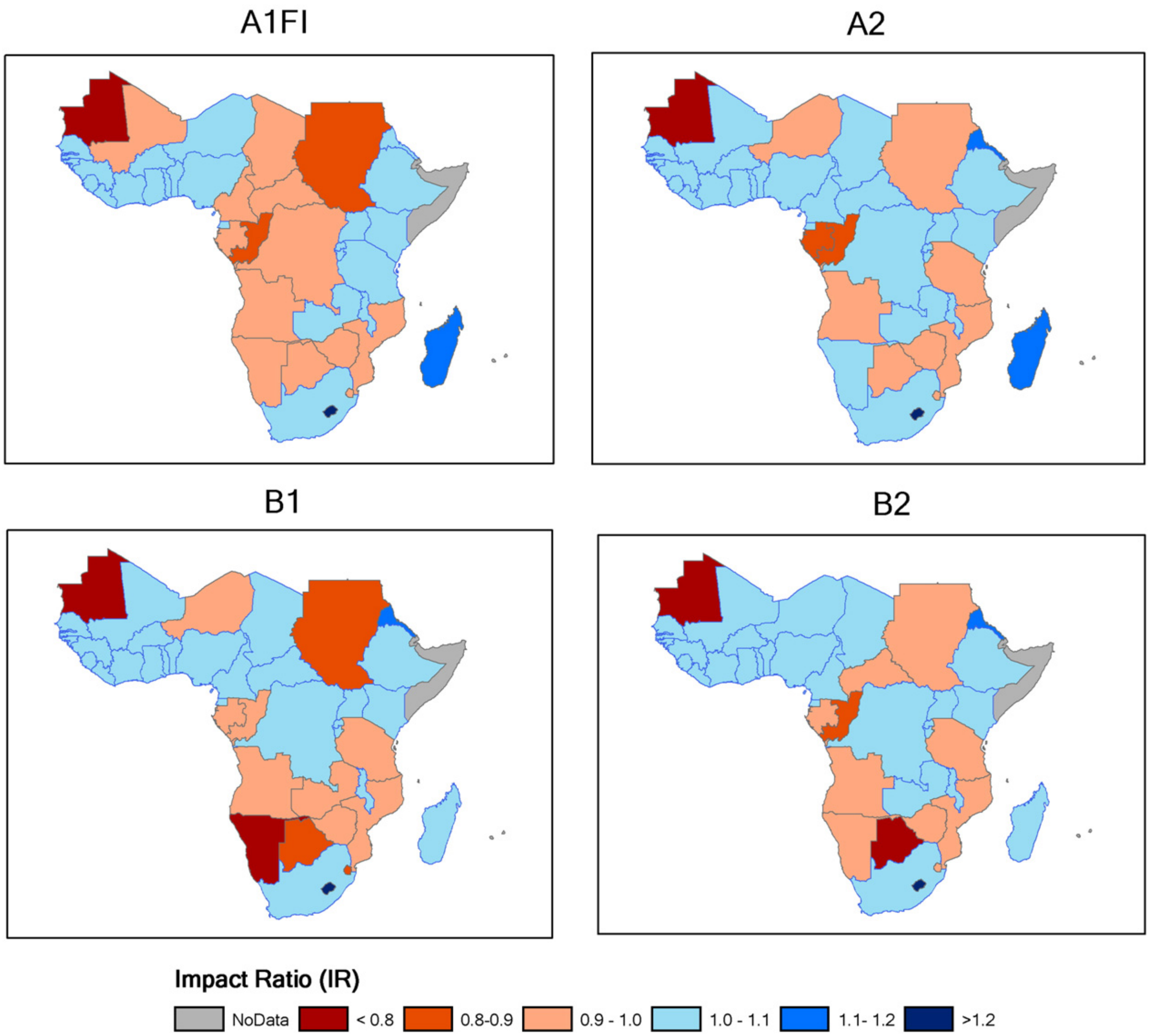

Fig. 10. National average impact ratio of climate change on crop production in Sub-Saharan Africa for A1FI, A2, B1 and B2 scenarios.

3.5. Comparison of current hotspots of undernutrition with future potential hotspots of food insecurity in the 2030s

As outlined in Section 2.4 we identify the future hotspots of food insecurity by identifying those grid cells where per capita availability of calorie will decrease and the growth rate of per capita GDP will be below the world average between the 1990s and the 2030s. Two hotspot classes are categorized. In both classes, the capacity of being able to import food will decrease between the 1990s and the 2030s. In the first class (hotspot), per capita calorie availability decreases by 0–30%, while in the second class (severe hotspot), per capita calorie availability decreases by over 30%. Grid cells of the hotspot is shown single shaded in Fig. 13, while grid cells of the severe hotspot are shown in Fig. 13 cross-shaded. We also examine how these potential hotspots are related to the current undernutrition hotspots. Such a comparison allows us to identify areas where more effort is needed in terms of future actions (such as food aid and development programs).

The results show that, for densely populated regions (population density>20,000 people/km^2), regions in northern and southwestern Nigeria, Sudan and Angola with a currently high number of people with undernutrition might be able to improve their food security situation due to either an increase in per capita calorie availability or an increase in the capacity to import food. Other regions located in Ethiopia, Uganda, Rwanda, Burundi, southwestern Niger, and Madagascar with current undernutrition problems will likely remain hotspots of food insecurity in the future. In these regions, the capacity to import food will be lower in the future, while per capita calorie availability will be reduced by 0–30%. Regions located in Tanzania, Mozambique and the Democratic Republic of Congo might face more serious undernutrition in the future. These regions will have a lower capacity to import food in the future, while per capita calorie availability will be reduced by over 30%.

4. Conclusion

This paper deals with a spatially explicit assessment of current and future hotspots of food insecurity in Sub-Saharan Africa (SSA). The number of people suffering from undernutrition is assessed with a spatial resolution of 30 arc-minutes. The impact of climate change on crop production is analyzed for six major crops in SSA with the same spatial resolution. The hotspots of future food insecurity are identified in the context of future global changes in population, GDP, and crop production.

The results show different patterns of yield change for six major crops in SSA. Wheat will have a sharp reduction in crop yield, while the yield of millet will increase due to climate change. The yield of other crops will be less affected by climate change than these two crops. However, when taking population growth into account, most

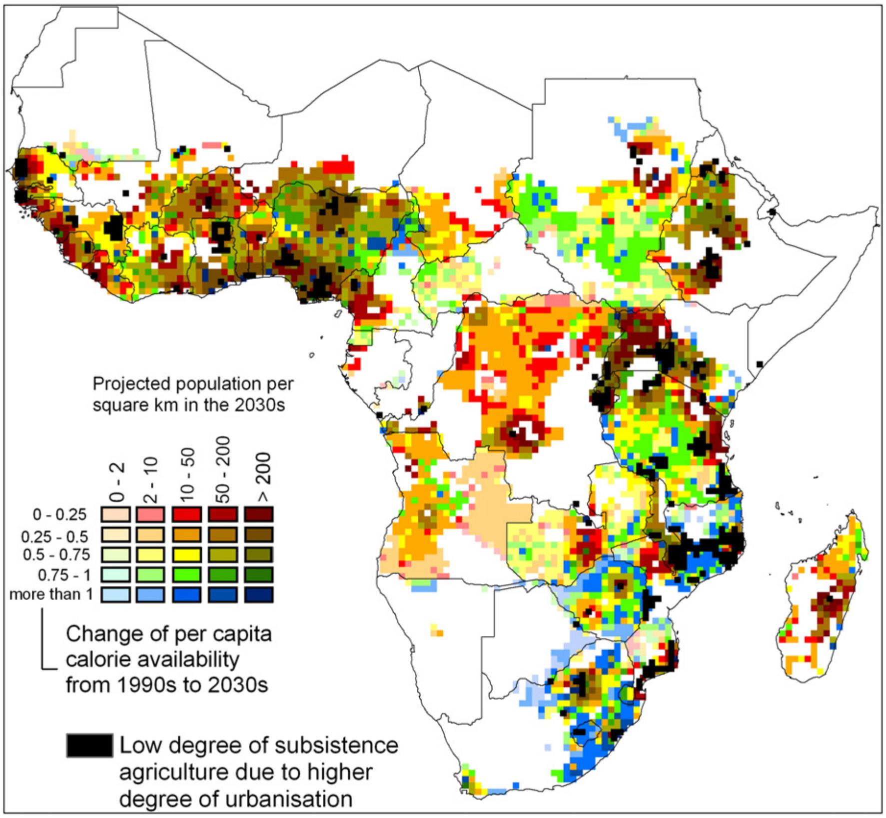

Fig. 11. Changes of per capita calorie availability from the 1990s to the 2030s in relation to population density of the 2030s and low degree of subsistence agriculture. For change of per capita calorie availability, the legend 0–0.25 means a reduction of 100–75%, 0.25–0.5 means a reduction of 75–50%, 0.75–1 means a reduction between 25 and 0%, and more than one means that per capita calorie availability will increase between the 1990s and the 2030s. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

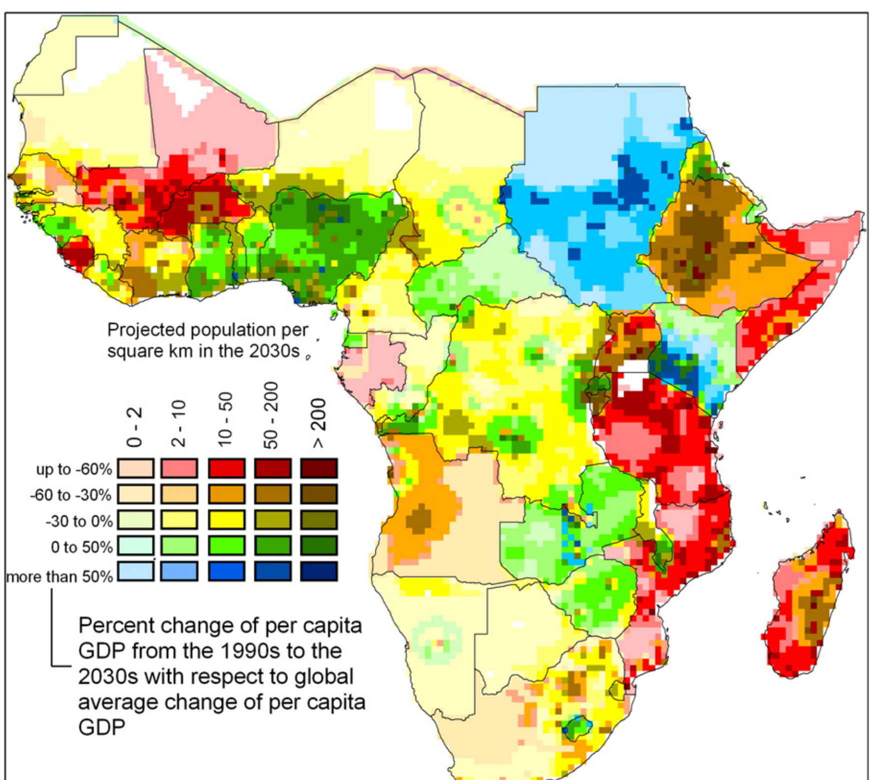

Fig. 12. Changes in per capita GDP from the 1990s to the 2030s in relation to projected population density in the 2030s. A positive percentage in the legend indicates a higher growth rate of GDP than the world average growth rate between the 1990s and the 2030s. For instance, the value of 50% means the growth rate of GDP is 50% higher than the world average growth rate (i.e. 3.6%), or it means the growth rate of GDP is 5.4%. A negative percentage in the legend indicates a lower growth rate of GDP than the world average growth rate between the 1990s and the 2030s. For instance, the value of −30% means the growth rate of GDP is 30% lower than the world average growth rate, or it means the growth rate of GDP is 2.52%.

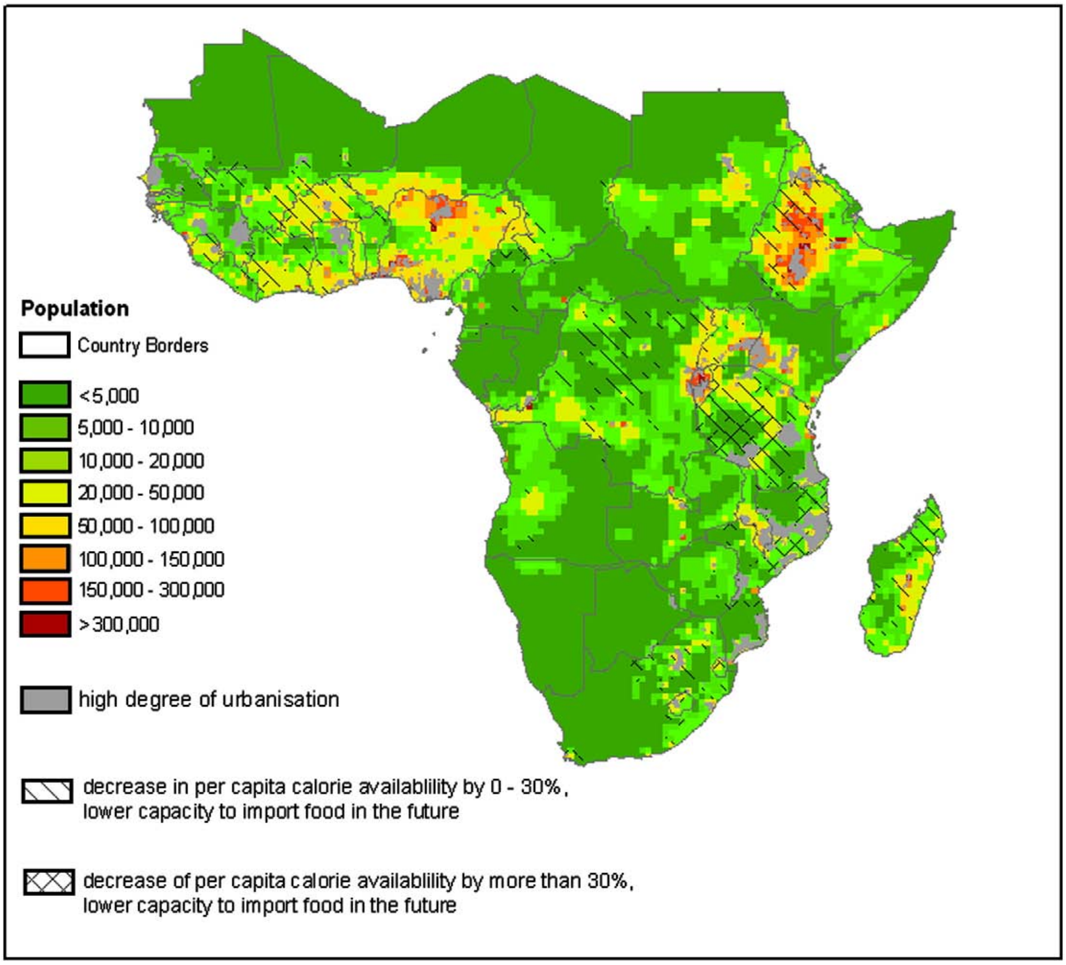

Fig. 13. Number of people with current undernutrition problems in relation to future potential hotspots of food insecurity in the 2030s.

African countries will experience lower per capita calorie availability in the future. By considering spatially explicit information on per capita GDP, we conclude that certain regions such as central–northern Ethiopia, southern Uganda, southwestern Niger, northern Tanzania, and countries such as Rwanda and Burundi will most likely continue to be trapped in poverty.

On the other hand, other regions located in southwestern Niger, Nigeria and Sudan are predicted to be able to import more food and might therefore manage to reduce food insecurity. However, special attention has to be paid to countries such as Tanzania, Mozambique and the Democratic Republic of Congo because these countries are predicted to face more serious undernutrition in the future as both the capacity to import food and the per capita calorie availability are predicted to be lower in the future.

In this scenario study we intentionally consider limited adaptive capacity trying to reflect some of the constraints of subsistence agriculture under extreme poverty. The study intentionally does not consider new crop distributions such as the replacement of sorghum by maize and vice versa, or the use of new crop varieties which are more adapted to harsher climate conditions. Alternative crop management options such as irrigation are also not considered. However, we account for adaptations in the crop calendar. The research is therefore seen to show the current baseline under business as usual and considering future climate chance only — hence people will stick to the location and current distribution of current crop types and crop varieties. This in some way is a limitation of the study as people might change to other crops. Therefore we intend to consider alternative scenarios of higher adaptive capacities in a follow up study. We would then simulate what crops grow best in certain areas and in which regions crop acreage can be extended.

This paper is constrained by several limitations. First, although four climate scenarios are used, only results from one climate model, or the HadCM3 model, are used for the simulation of climate change on crop production. Projections of climate change have high uncertainty, and results simulated with climate data from other models may provide a different picture of the effect of climate change. Future research needs to combine climate scenarios from more climate models for a more comprehensive study. Second, there may also be uncertainties in the spatially explicit data on future GDP and population. Third, the criteria of identifying the hotspots of food insecurity contain certain subjective elements as certain thresholds have to be chosen when comparing current with future hotspots. Despite these limitations, we have made the first attempt to address the spatially explicit assessment of the current and future hotspots of food insecurity in SSA. The results can provide valuable information for decision makers to set priority areas to combat hunger in SSA.

The study indicates that dramatic adaptive measures need to be taken in the next 30 years to improve the situation of food security in SSA. The spatially explicit assessment allows targeting the areas where urgent actions are needed to prevent future hunger. These actions range from improving crop varieties, optimizing crop types, extending crop area, and increasing crop yield through better water and fertilizer management. In case that the adaptive measures are not taken, several countries such as Tanzania, Mozambique and the Democratic Republic of Congo will continue to remain highly food insecure. International food aid is a necessity to help enhance the food security in these countries when adaptive measures fail.

Acknowledgements

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References

Adejuwon, J.O., 2006. Food crop production in Nigeria. II. Potential effects of climate change. Clim. Res. 32 (3), 229–245.
Batjes, N.H., 2006. ISRIC-WISE derived soil properties on a 5 by 5 arc-minutes global grid. International Soil Reference and Information Centre (ISRIC), Wageningen, the Netherlands.
Brown, M.E., Funk, C.C., 2008. Climate: food security under climate change. Science 319 (5863), 580–581.
Challinor, A., Wheeler, T., Garforth, C., Craufurd, P., Kassam, A., 2007. Assessing the vulnerability of food crop systems in Africa to climate change. Clim. Change 83 (3), 381–399.
DHS, 2006. Demographic and Health Surveys, Measure DHS+. Macro International Inc., Calverton, USA.
FAO, 1999. Food insecurity: when people must live with hunger and fear of starvation, The State of Food Insecurity in the World. Food and Agriculture Organization of the United States, Rome.
FAO, 2006a. FAOSTAT: FAO statistical databases. Food and Agriculture Organization of the United Nations, Rome.
FAO, 2006b. Food security statistics, FAO Statistics Division. Food and Agriculture Organization of the United Nations, Rome, Italy.
Gordon, C., et al., 2000. The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Clim. Dyn. 16 (2–3), 147–168.
Grübler, A., et al., 2007. Regional, national, and spatially explicit scenarios of demographic and economic change based on SRES. Technol. Forecast Soc. Change 74 (7), 980–1029.
IFPRI, 2004. Ending Hunger in Africa: Prospects for the Small Farmer. International Food Policy Research Institute, Washington, D.C.
IPCC, 2001. Climate change 2001: the scientific basis. Contribution working group I to the third assessment report of the IPCC. Cambridge University Press, Cambridge.
Jones, P.G., Thornton, P.K., 2003. The potential impacts of climate change on maize production in Africa and Latin America in 2055. Glob. Environ. Change 13 (1), 51–59.
Liu, J., in press. A GIS-based tool for modelling large-scale crop-water relations. Environ. Modell. Softw. doi:10.1016/j.envsoft.2008.08.004.
Liu, J., Savenije, H.H.G., 2008. Food consumption patterns and their effect on water requirement in China. Hydrol. Earth Syst. Sc. 12 (3), 887.
Liu, J., Wiberg, D., Zehnder, A.J.B., Yang, H., 2007a. Modelling the role of irrigation in winter wheat yield, crop water productivity, and production in China. Irrig. Sci. 26 (1), 21–33.
Liu, J., Williams, J.R., Zehnder, A.J.B., Yang, H., 2007b. GEPIC — modelling wheat yield and crop water productivity with high resolution on a global scale. Agric. Sys. 94 (2), 478–493.
Liu, J., Zehnder, A.J.B., Yang, H., 2008. Drops for crops: modelling crop water productivity on a global scale. Glob. NEST J. 10 (3), 295–300.
Liu, J., Williams, J.R., Wang, X., Yang, H., in press. Using MODAWEC to generate daily weather data for the EPIC model. Environ. Modell. Softw. doi:10.1016/j.envsoft.2008.10.008.
Lobell, D.B., et al., 2008. Prioritizing climate change adaptation needs for food security in 2030. Science 319 (5863), 607–610.
Mitchell, T.D., Jones, P.D., 2005a. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int. J. Climatol. 25 (6), 693.
Mitchell, T.D., Jones, P.D., 2005b. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int. J. Climatol. 25 (6), 693–712.
Nube, M., 2001. Confronting dietary energy supply with anthropometry in the assessment of undernutrition prevalence at the level of countries. World Dev. 29 (7), 1275.
Nube, M., Van Den Boom, G.J.M., 2003. Gender and adult undernutrition in developing countries. Ann. Hum. Biol. 30 (5), 520–537.
Parry, M., Rosenzweig, C., Iglesias, A., Fischer, G., Livermore, M., 1999. Climate change and world food security: a new assessment. Glob. Environ. Change 9 (Supplement 1), S51–S67.
Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M., Fischer, G., 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Glob. Environ. Change 14 (1), 53–67.
Pope, V.D., Gallani, M.L., Rowntree, P.R., Stratton, R.A., 2000. The impact of new physical parametrizations in the Hadley Centre climate model: HadAM3. Clim. Dyn. 16 (2–3), 123–146.
Reilly, J.M., Schimmelpfennig, D., 1999. Agricultural impact assessment, vulnerability, and the scope for adaptation. Clim. Change 43 (4), 745–788.
Reilly, J., Schimmelpfennig, D., 2000. Irreversibility, uncertainty, and learning: Portraits of adaptation to long-term climate change. Clim. Change 45 (1), 253.
Rosegrant, M., Cai, X., Cline, S., Nakagawa, N., 2002. The role of rainfed agriculture in the future of global food production. International Food Policy Research Institute, Washington, D.C.
Rosenzweig, C., Parry, M.L., 1994. Potential impacts of climate change on world food supply. Nature 367, 133–138.
Sanchez, P.A., Swaminathan, M.S., 2005. Hunger in Africa: the link between unhealthy people and unhealthy soils. The Lancet 365 (9457), 442–444.
Stockle, C.O., Williams, J.R., Rosenberg, N.J., Jones, C.A., 1992. A method for estimating the direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: Part I-Modification of the EPIC model for climate change analysis. Agric. Syst. 38 (3), 225–238.
Svedberg, P., 1999. 841 million undernourished? World Dev. 27 (12), 2081.
UN Millennium Project, 2005. Halving hunger: it can be done. Earthscan, London, 242 pp.
UNICEF, 1990. Strategy for improved nutrition of children and women in developing countries. A UNICEF policy review. United Nations Children's Fund, New York, USA.
Von Braun, J., et al., 2005. New risks and opportunities for food security. International Food Policy Research Institute, Washington D.C.
WHO, 1995. Physical Status: the Use and Interpretation of Anthropometry. Technical Report Series 854. World Health Organization, Geneva, Switzerland.
WHO, 1999. Nutrition for health and development. Progress and prospects on the eve of the 21st century. World Health Organization, Geneva.
WHO, 2006. Adolescent Nutrition: a Review of the Situation in Selected South-East Asian Countries. SEA-NUT-163. World Health Organization. Regional Office for South-East Asia, New Delhi.
Williams, J.R., Jones, C.A., Kiniry, J.R., Spanel, D.A., 1989. The EPIC crop growth model. Trans. ASAE 32, 497–511.
World Bank, 1986. Poverty and hunger: issues and options for food security. A World Bank policy study. World Bank, Washington, DC.

Towards a dynamic stochastic model of pandemic influenza

P. Brunovský S. Kilianová

1 Introduction

This study represents a continuation of the analysis of the socio-economic impact of various mitigation scenarios of pandemic influenza mitigation of [1]. Unlike in [1], we are interested in the timing of the mitigation measures. Along the lines of GeoBene, our ultimate goal is to assess the measure of observation of the development of the pandemia. In this respect, our study bears some similarities to the one by [3]. This program requires a dynamic model of pandemic influenza describing its time development. We believe that, due to the complex nature of the spread of the infection the standard deterministic SIR model [2] is not adequate. Therefore, we adopt the philosophy of [1], [3] stochastic simulation based on a stochastic difference equation. A particular difficulty with influenza is that most of the relevant parameters (like the duration and intensity of infecteveness of a sick individual) are not known and experts differ in their opinions. Therefore, one of our goals is to estimate them inversely from generally adopted cumulative data like clinical attack rate.

2 The model

We make the following assumptions:

- the population is homogenenous;
- an infected infividual is infective for 4 days;
- the intesity of contacts of an infected individual to susceptibe ones depends on the duration of his sicknes - the loger he is infected, the more likely he becomes isolated;
- an infected individual becomes immune to a repeated infection during the course of the pandemia.

By the number of contacts K we understand the number of people one meets to an infective distance within one time unit - a day. By T we denote the duration of the infectiveness of an infected individual. According to our assumptions we take $T = 4$. By I_t^{new} we denote the number of people who become infectious at time t, $I_t = \sum_0^t I_t^{new}$, by $S_t = S_0 - I_t$ the number of susceptibles, S_0 being given. Then the overall number of infectious at time $t > T$ is $\sum_{\tau=0}^{T-1} I_{t-T+\tau}^{new}$. Hence, the number K_t of contacts of a susceptible with infectious humans infected at the day $t - T + \tau$ is given by

$$K_{t,\tau} = K \frac{I_{t-T+\tau}^{new}}{N_t - 1} \xi_{T-\tau} \tag{1}$$

where $\xi_{T-\tau}$ represents a measure of isolation of an infected human as a function of his disease-age τ. It is natural to assume that the sequence $\{\xi_1, ..., \xi_T\}$ is decreasing and $\xi_1 = 1$. Recall that ξ_t is not defined for $t > T$ since an infected individual is not infective after T days anymore. The probability p_t that a susceptible becomes infected at the time t is then given by

$$p_t = 1 - (1 - \beta)^{\sum_{\tau=0}^{T-1} K_{t,\tau}} . \tag{2}$$

where β is the probability that when a susceptible comes into contact with an infectious, he becomes infected. The population dynamics can be described by the equation

$$I_{t+1} = I_t + I_t^{new}, \tag{3}$$

where I_t^{new} is a random variable with the binomial distribution, i.e. $I_t^{new} \sim Bin(S_0 - I_t, p_t)$ where $p_t = p_t(I_{t-T}^{new}, \ldots, I_{t-1}^{new})$ is given by (2).

3 Simulations

Following [1] we take the clinical attack rate of the influenza virus at the level of 30% of the overal population. We calibrated the model with the goal of satisfying this rate approximately. We consider $\beta = 0.082$, $K = 5$, overal population size $N = 5400000$. The size of prevaccinated population $0.15N$ is excluded from the population S_0 of susceptibles, i.e. $S_0 = 0.85N$. The duration of being infectious is fixed at $T = 4$. The isolation sequence is set as $\{\xi_1, ..., \xi_4\} = \{1, 1, 0.7, 0.2\}$. The starting state was $I_1^{new} = 10$ infectious at the beginning of the considered period of 350 days. The results of 100 simulations are presented in Figure 1 and Table 1. We can read out from the graphs that the approximate duration of aggresive propagation of the virus in the country is about 2 months.

As a brief experiment on sensitivity analysis we considered $\beta = 0.08$ and other parameters as before. As a result, the overall number of infected decreased to $\mathbb{E}(I_{350}) = 1475199.75$ and the maximum number of new infected through all days and all simulations to $\max I_t^{new} = 25403$. Hence, a small change in the value of the

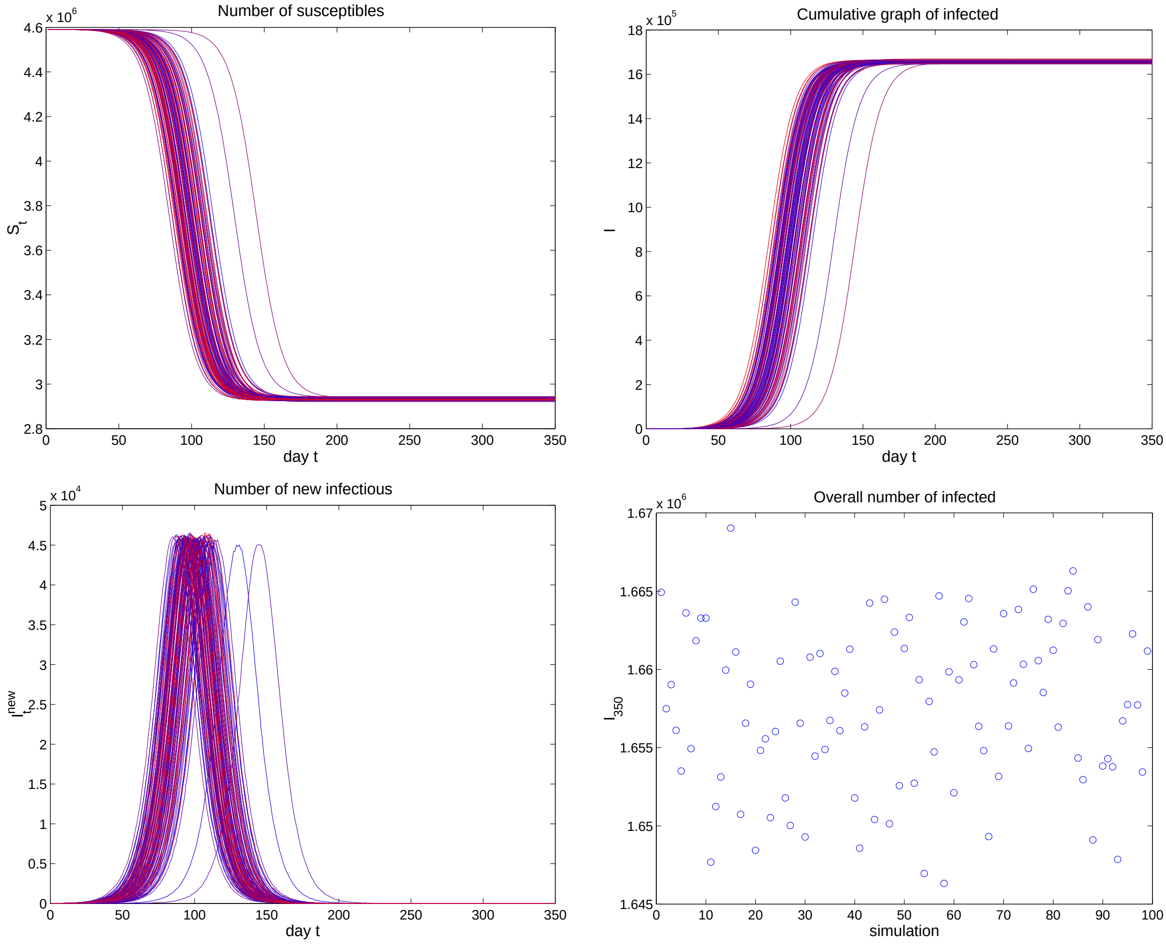

Figure 1: Results of 100 simulations. Graphs of (a) susceptibles S_t, (b) cumulative number of infected I_t, (c) new infected I_t^{new} at particular time and (d) the overall number I_{350} of infected.

$E(I_{cum})$	1640864.06
$Var(I_{cum})$	27497195301.9
$\max I_t^{new}$	46561

Table 1: Characteristics obtained from 100 simulations, $\beta = 0.082$, $T = 4$, $K = 5$.

β parameter caused that the maximum number of new infected at one time unit changed significantly. This information is important in order to be able to secure sufficient capacity of medical care. Therefore, it is of high importance to estimate the β parameter as precisely as possible.

Simulations were performed in the Matlab R12 environment. The duration of the computation of 100 simulations was approximately 3.2 hours.

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References

[1] P. Brunovský, D. Ševčovič, J. Somorčík, D. Hroncová, K. Pospíšilová: Socio-economic impacts of pandemic influenza mitigation scenarios in Slovakia, Journal of Economics 57(2009), 163–178

[2] O. Diekmann, J. A. P. Heesterbeek: Mathematical Epidemiology Of Infectious Diseases: Model Building, Analysis And Interpretation. John Wiley and Sons (2000)

[3] Z. Chladná, E. Moltchanova: The Value of Observations in Determination of Optimal Vaccination Timing and Threshold. Working paper.

Socio-economic Impacts of Pandemic Influenza Mitigation Scenarios in Slovakia[1]

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Abstract

The aim of this paper is to assess the expected socio-economic impacts of various scenarios of pandemic influenza mitigation on the economy and mortality for Slovakia. Compared to similar past studies (e.g. Van Genugten et al. (2003)), our approach bears a significant difference. Whereas those studies work from the very beginning with the expected values of the data, we have treated the data as well as the model parameters as random variables. Results in the form of probability distributions and their characteristics (expected values and tolerance intervals) were obtained by stochastic Monte Carlo simulations of random impacts on 5,400,000 inhabitants of Slovakia. Six scenarios of pandemia mitigation have been analyzed. Total costs of medical treatment, the number of casualties as well as social costs with casualties included were compared.

Keywords: *pandemia, influenza, Monte Carlo, mitigation*

JEL Classification: I18, C15

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Introduction

Influenza pandemics can occur when a novel strain of flu virus causes epidemics that spreads very fast worldwide and affects high proportion of the world population. There have been 31 influenza pandemics recorded since 1580 (Lazzari and Stőhr, 2004). Reliable epidemiological data are sparse until the pandemics in 1889 – 1992. Most knowledge about the epidemiology of pandemic influenza can be obtained from the three well-documented pandemics of the 20th century in 1918 – 1919, 1957 – 1958 and 1968 – 1969 (Beran and Havlík, 2005). They represent the main source of evidence on the potential human toll of the next pandemic. The intervals between the consecutive pandemics of the 20th century ranged from 11 to 40 years. It has now been 40 years since the occurrence of the last pandemic in 1968. In 1997, the avian influenza virus H5N1 was shown to infect humans directly. As of 10 September 2008, 387 human cases of avian flu have been reported by WHO (World Health Organisation), 245 of which were fatal. Case fatality has reached over 60% (WHO, 2008a). At present, WHO confirmed few cases of human-to-human transmission of H5N1 (WHO, 2008b).

Increased awareness on influenza pandemics has led to discussions held by WHO, public health authorities, regulatory authorities, pharmaceutical industry on what our society can do and also should do to be prepared for the next pandemic. In a number of countries pandemic influenza plans have been drafted with several alternatives of mitigation scenarios that should decrease the health impacts including severe mortality and death and to minimize the social and economical impact of the next pandemic. Reports on the expected outcomes of such scenarios can be found e. g. in recent papers by Van Genugten et al. (2003), German et al. (2006), Fraser et al. (2004), Longini et al. (2005), Ferguson et al. (2006).

The present paper represents an analysis of the impacts of several mitigation scenarios for the country of Slovakia. However, while the papers cited above work merely with expected values, we take into account entire probability distributions of the variables. A similar approach has been employed by Meltzer et al. (1999) as well as Doyle et al. (2006). However, whereas in the cited papers uncertainty is restricted to the mitigation variable, we admit all probability parameters to be of stochastic nature. Further, instead of triangular or uniform distributions we work with more adequate beta ones (see below).

This approach is much more computationally involved but also more informative: in addition to the expected values of the outcomes it yields their entire probabilistic distributions and, hence, e.g. the value of risk coming from uncertainty of their predictions.

1. The Simulation Model and its Parameters

1.1. Input Parameters and Scenarios

The data in the Table 1 below have been taken from accessible literature. They have been consulted with specialists from pharmaceutical and health insurance companies.

Table 1

Parameters of the Influenza Mitigation Model for the Case of Slovakia

Number of inhabitants	5,400,000
Influenza clinical attack rate	30%
Influenza mortality	2.5%
Percentage of infected medically treated	50%
Clinical complications rate of medically treated	25%
Percentage of infected hospitalized	8%
Percentage of infected hospitalized at ICU	2%
Antivirotics price	26.55 Euro
Price of complications treatment drugs	6.63 Euro
Standard hospitalization costs	464.7 Euro
ICU hospitalization costs	995.8 Euro
Pandemic vaccine price	7.83 Euro
Pre-pandemic vaccine price	7.83 Euro

Note: ICU abbreviates the Intensive Care Unit.

Sources: Fraser et al. (2004) – line 2, Taubenberger et al. (1999) – line 3, Van Genugten et al. (2003) – line 4, Leroux et al. (2007), Longini et al. (2005), WHO (2008a) – lines 5 – 7, authors' estimates – lines 12, 13, public sources – lines 1, 8 – 11.

We have simulated six different scenarios of influenza mitigation:

1. No vaccination (so-called control).
2. Whole population pre-vaccination (i.e. 2x pre-pandemic vaccination + 1x pandemic).
3. 2x pandemic vaccination of 50% population.
4. 2x pre-pandemic vaccination of whole population.
5. Pre-vaccination of 35% population + 2x pandemic vaccination of 32.5% population.
6. 1x pre-pandemic + 1x pandemic vaccination of the entire population.

The expected vaccine efficacy could be found in Table 2.

Table 2

Vaccination Efficacy (in %)

Pre-vaccination	**70**
2x pandemic	80
2x pre-pandemic	60
1x pre-pandemic + 1x pandemic	65

Sources: WHO (2008b) – line 1, authors' estimates – lines 2 – 4.

The figures 1 – 8 represent the decrease of the influenza clinical attack rate due to type of vaccination.

1.2. Simulation principle

To simulate particular scenarios the computer "infected" each individual of the population of 5,400,000 with the probability corresponding to the scenario, hence the distribution of infected individuals was binomial:

$$\text{number of infected people} \sim \text{Bin}(n, p_{car})$$
$$n = 5{,}400{,}000 \quad p_{car} = \text{specific clinical attack rate}$$

where

$$\text{specific clinical attack rate} = \text{clinical attack rate}\,.\,(1 - \text{vaccination efficacy}).$$

Recall that a discrete random variable X has a binomial (or Bernoulli) distribution $\text{Bin}(n, p)$ with parameters $n \in N$ and $p \in [0,1]$, if the probability $\text{Prob}(X = k)$ satisfies

$$\text{Prob}(X = k) = \binom{n}{k} p^k (1-p)^{n-k}$$

The binomial distribution is the discrete probability distribution of the number of successes in a sequence of n independent random yes/no experiments, each of which is successful with probability p between 0 and 1.

In case of Scenarios 3 and 5 the population has been partitioned into vaccinated/non-vaccinated and "infection" was carried out in each group separately. Then, for each infected person the computer generated (randomly with corresponding probability) whether she/he has been medically treated or not: thus, the number of treated individuals had a binomial distribution:

$$\text{number of treated people} \sim \text{Bin}(n_{\text{inf}}, p_{mt})$$
$$n_{\text{inf}} = \text{number of infected people}, \quad p_{mt} = \text{probability of medical treatment.}$$

We have assumed that each treated person has received antivirotics and in case of complications (the computer generated their occurrence) other drugs as well. The distribution of the number of complications has been taken as binomial as well:

$$\text{number of complications} \sim \text{Bin}(n_{\text{inf}}, p_{ccr})$$
$$n_{\text{inf}} = \text{number of infected people}, \; p_{ccr} = \text{clinical complications rate.}$$

For an infected individual the computer has generated whether he/she would has been subject to (standard or ICU) hospitalization or not:

$$\text{number of hospitalizations} \sim \text{Bin}(n_{\text{inf}}, p_{sh})$$
$$n_{\text{inf}} = \text{number of infected people}, \; p_{sh} = \text{probability of standard hospitalization;}$$

$$\text{number of ICU hospitalizations} \sim \text{Bin}(n_{\inf}, p_{icu})$$

$n_{\inf}$ = number of infected people, p_{icu} = probability of the ICU hospitalization.

Eventually, for each infected person the computer generated whether she/he has survived the infection or not:

$$\text{number of deaths} \sim \text{Bin}(n_{\inf}, p_d)$$

$n_{\inf}$ = number of infected people, p_d = probability of death·

To summarize we have confronted the numbers of infected, medically treated, hospitalized (hospitalized in ICUs, in particular) and dead individuals. The costs of vaccination, drugs and hospitalization have been calculated as follows:

$$\begin{aligned}\text{vaccination costs} &= (\text{number of prepandemic vaccines}) \times (\text{prepandemic vaccine price}) \\ &+ (\text{number of pandemic vaccines}) \times (\text{pandemic vaccine price});\end{aligned}$$

$$\begin{aligned}\text{drug costs} &= (\text{number of treated people}) \times (\text{ antivirotics price}) \\ &+ (\text{number of complicat}\cdot) \times (\text{cost of drugs for complications});\end{aligned}$$

$$\begin{aligned}&\text{hospitalization costs } = \\ &= (\text{number of standard hospitalizations}) \times (\text{standard hospitalization cost}) \\ &+ (\text{number of hospitalized in ICU}) \times (\text{price of ICU hospitalization}).\end{aligned}$$

The total costs are obtained by summing up all the above costs:

$$\text{total costs} = (\text{vaccination costs}) + (\text{drug costs}) + (\text{hospitalization costs}).$$

The procedure described above (i.e. an individual simulation of pandemic influenza) has been repeated 10,000 times for each of the 6 scenarios. This has given us an interval in which, for a given scenario, one could expect particular outcomes (i.e. numbers of infected, dead, heights of costs of particular type, etc.) and which values would be the most probable ones. Notice that random data simulations we carried out for each individual lead to a time consuming computational procedure. Approximation of the binomial distribution by a normal one would not result in a noteworthy decrease of the time complexity of our Monte Carlo simulations.

1.3. Randomization of Input Parameters

The results of the simulations depend significantly on parameters of the input probabilities (represented by the percentage data in the Tables 1 and 2), the values of which are based on estimates of medical specialists. Therefore, we have considered these parameters as random ones: for each of the 10,000 Monte Carlo simulations of a particular scenario they have been generated by the computer from the Beta distribution having its probability density distribution function *f* defined as:

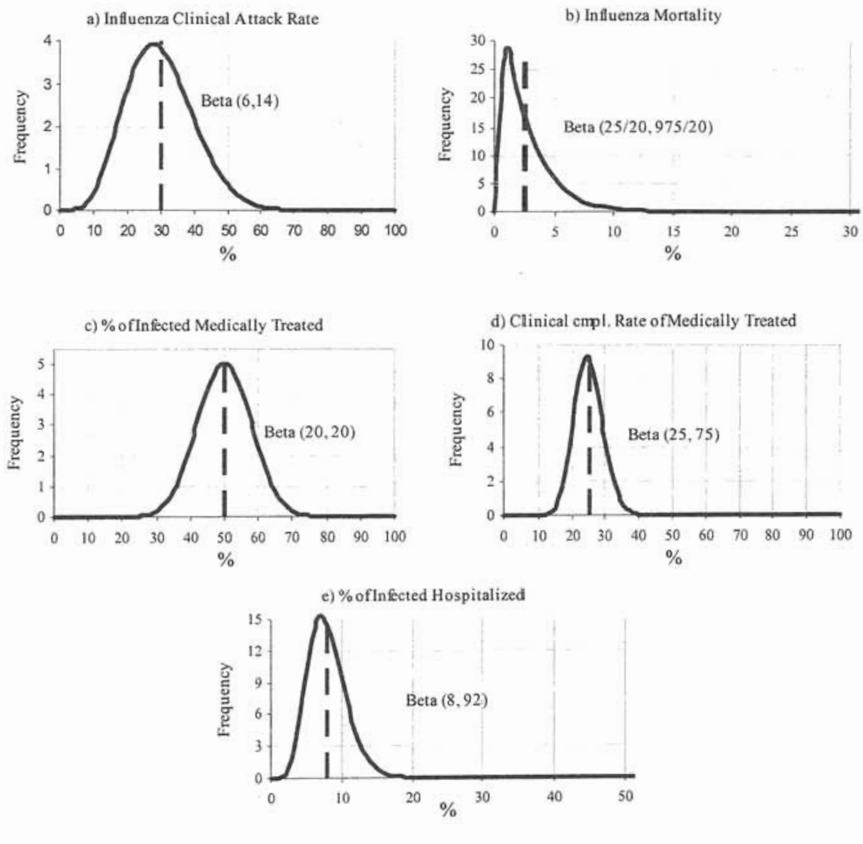
$$f(x)=\begin{cases} x^{\alpha-1}(1-x)^{\beta-1}/B(\alpha,\beta), & \text{if } x\in(0,1) \\ 0, & \text{otherwise} \end{cases}$$

where $B(\alpha,\beta)=\int_0^1 x^{\alpha-1}(1-x)^{\beta-1}dx$ is the Euler Beta function.

Recall that for an integer value of the parameter α the cumulative probability of the Beta distribution from 0 to x is the probability that at least α of the random variables are less than x, a probability is given by summing over the binomial distribution. We have therefore chosen the Beta distribution because of its relation to the Binomial distribution and because of its flexibility from the point of view of approximation of a wide class of distributions.

Figure 1

Model Parameters as Random Variables Generated by Beta Distributions



Note: The dashed vertical line represents the mean value taken from Table 1.

Source: Own results.

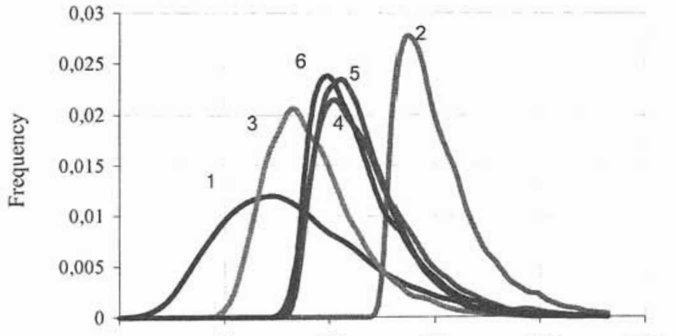
The particular Beta distribution has been chosen with expected value equal to the value in Table 1 or 2. The shape of the density of the particular Beta distribution reflects our subjective confidence in the values of the parameters of Table 1 and 2: in case we have chosen a wide peak Beta density, the computer generated values of the respective parameter with a large dispersion around the value in Table 1 or 2. This means that we do not trust much the value in Table 1 or 2 and admit deviations from it. On the other hand, a narrow Beta distribution density means that the generated values of parameter do not deviate significantly from the value in Table 1 or 2; this reflects our higher trust in the values of Table 1 and 2. Particular choices of the Beta distribution are depicted in Figure 1.

2. Results

2.1. Total Costs

In Figure 2 total costs of the six scenarios are compared. The graphs represent estimated densities of the costs of particular scenarios, vertical lines being their statistical frequencies.

Figure 2
Total Costs



Note: 1: no vaccination (so-called control); 2: whole population pre-vaccination (i.e. 2x pre-pandemic vaccination plus 1x pandemic); 3: 2x pandemic vaccination of 50% population; 4: 2x pre-pandemic vaccination of whole population; 5: pre-vaccination of 35% population plus 2x pandemic vaccination of 32.5% population; 6: 1x pre-pandemic plus 1x pandemic vaccination of whole population.

Source: Own results.

The location of the peak indicates where one can approximately expect total costs of a particular scenario. We see that the peaks of scenarios 2 to 6 are located to the right of the peak of scenario 1. This means that the expected value of scenario 1 is lower than the ones of any of remaining scenarios.

The height of the graph in a certain interval indicates how likely the costs in this interval are for a particular scenario. For example, under scenario 1 we see that costs in the interval 66 to 133 millions of Euro are much more likely than costs between 133 and 200 millions of Euro because the graph is much higher over the interval 66 to 133 millions than the corresponding graph over the interval 133 to 200 millions of Euro.

Important information is carried by the width of the peak. It informs about the dispersion of the expected costs: the wider the peak, the higher the uncertainty of the expected costs of the particular scenario. The width of the peak allows us to compare e. g. the scenarios 1 and 3 (Figure 2). From the point of view of mean expected values the scenarios are practically equivalent. However, the peak of the density of scenario 3 is considerably narrower which means that the costs of scenario 3 are much more predictable than those of scenario 1. The width of the peak can be characterized by the 95% tolerance interval that is, by definition, the interval including with 95% probability the total costs of the particular scenario. The results are summarized in Table 3. For the reader's convenience, let us recall the numbering of the scenarios:

1. No vaccination (so-called control).
2. Whole population pre-vaccination (i.e. 2x pre-pandemic vaccination + 1x pandemic).
3. 2x pandemic vaccination of 50% population.
4. 2x pre-pandemic vaccination of whole population.
5. Pre-vaccination of 35% population + 2x pandemic vaccination of 32.5% population.
6. 1x pre-pandemic + 1x pandemic vaccination of whole population.

Table 3
Total Costs

Scenario	Mean Value	Median	Tolerance Interval	Interval Width
1	86.3	79.6	from 30 to 169.3	139.4
2	152.7	146.0	from 129.5 to 205.8	76.3
3	92.9	89.6	from 59.7 to 146	86.3
4	119.5	112.8	from 89.6 to 179.2	89.6
5	112.9	109.5	from 86.3 to 159.3	73.0
6	112.9	109.5	from 86.3 to 169.3	83.0

Note: Mean value, median, 95% tolerance interval and interval width in millions of Euro.

Source: Own results.

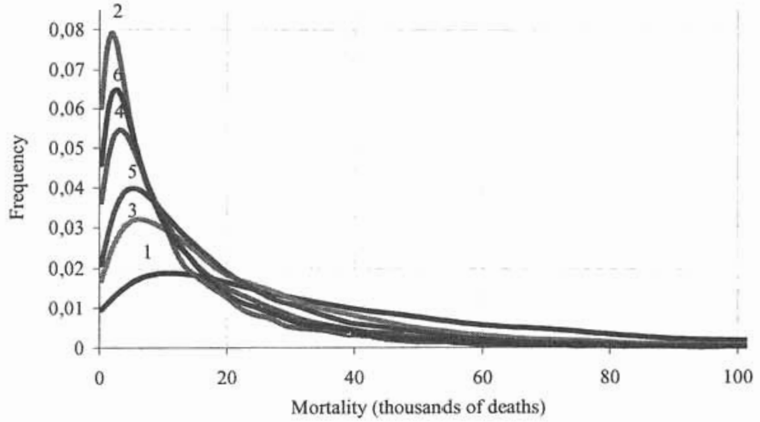
One can see that lowest mean costs can be expected under scenario 1 (i.e. without intervention) whereas the highest mean costs can be expected under scenario 2 (i.e. pre-vaccination of the total population). Scenario 2, on the other hand, is the best from the point of view of the expected dispersion: its estimated density in Figure 2 has the narrowest peak, and therefore the smallest tolerance interval. The reason is that by the expensive pre-vaccination (which is primarily responsible for the high total costs) the unpredictability of the course of infection of the population is lowered. As a result of pre-vaccination the vulnerability to infection of the population drops considerably and so do the random costs of medical treatment and hospitalization that are exclusively responsible for the dispersion.

However, the lowest costs of scenario 1 are misleading. Undoubtedly, this scenario has the widest peak of the estimated costs and the widest tolerance interval. This means that the total costs of scenario 1 may deviate considerably from their mean value. So, the lowest mean of scenario 1 is outweighed by a significant uncertainty due to uncertainty of the costs.

2.2. Mortality

An analysis similar to the one of total costs has been carried out for mortality. Figure 3 compares scenarios 2 to 6 with the non-interventional scenario 1.

Figure 3
Mortality



Note: 1: no vaccination (so-called control); 2: whole population pre-vaccination (i.e. 2x pre-pandemic vaccination plus 1x pandemic); 3: 2x pandemic vaccination of 50% population; 4: 2x pre-pandemic vaccination of whole population; 5: pre-vaccination of 35% population plus 2x pandemic vaccination of 32.5% population; 6: 1x pre-pandemic plus 1x pandemic vaccination of whole population.

Source: Own results.

The graphical plots in Figure 3 are statistically summarized in Table 4. It can be seen that scenario 2 appears as optimal. The average number of deaths as well as its dispersion appears to be the lowest (i.e. the peak of the distribution density is the lowest and the tolerance interval are the narrowest ones). The opposite extreme is represented by the non-interventional scenario 1: it has the highest average number of deaths and, more importantly, an extremely large dispersion, which means significant planning uncertainty (of e.g. medical care costs).

Table 4

Number of Deaths

Scenario	Mean	Median	Tolerance Interval	Interval Width
1	40.9	28.7	from 1.7 to 153.3	151.6
2	12.3	6.7	from 0.2 to 57.6	57.4
3	24.3	16.7	from 1.0 to 89.7	88.7
4	16.4	9.7	from 0.4 to 71.9	71.5
5	19.8	13.7	from 0.9 to 74.2	73.2
6	14.4	8.2	from 0.3 to 64.4	64.1

Note: Mean, median, 95% tolerance interval and interval width in thousands.

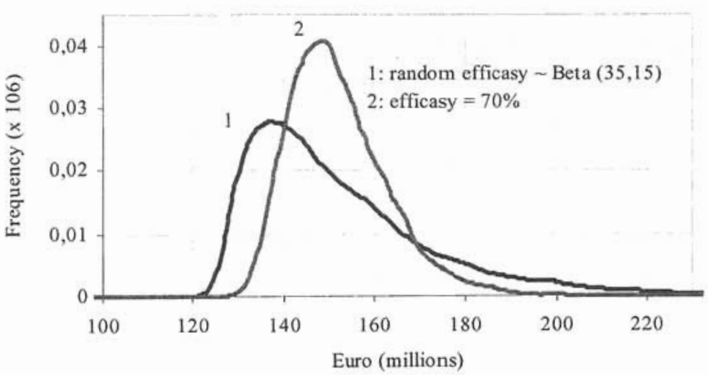
Source: Own results.

2.3. The Impact of Parameter Uncertainty

The widths of the peaks of the total costs and the number of deaths are determined by our trust in the input parameters. None of the values of the parameters we have considered is certain. This is why we have modelled them by a Beta distribution around the reference value. The dispersion of the Beta distribution reflected our trust in the reference value (smaller dispersion reflects more trust). The decrease of the uncertainty of the input parameter (i.e. decrease of dispersion of the corresponding Beta distribution) would decrease the dispersion of the output parameters (e.g. total costs, number of death, etc.).

Figure 4

Total Costs under Random/Fixed Pre-vaccination Efficacy



Source: Own results.

As an example we consider "pre-vaccination efficacy" and the impact of its dispersion on the dispersion of the total costs of scenario 2 (i.e. pre-vaccination of the total population). Normally, the pre-vaccination efficacy has been generated from the Beta (35,15) distribution (cf. Figure 1), the mean of which is 70%, the reference value from Table 2. We have carried out additional simulations of the pandemic impacts under scenario 2: the pre-vaccination efficacy has been set to exactly 70%. That is, we have trusted to this value absolutely, its dispersion having been zero. Figure 4 and Table 5 show a decrease of the dispersion of total costs that can be considered as an advantage.

Table 5

Total Costs under Random/Fixed Pre-vaccination Efficacy

Efficacy	Mean	Median	Tolerance Interval	Interval Width
Random	152.7	146	from 129.5 to 205.8	76.3
Fixed	152.7	149.4	from 136 to 175.9	39.8

Note: Mean value, median, 95% tolerance interval and interval width in millions of Euro.
Source: Own results.

We see that a decrease of the parameter dispersion yields improved (i.e. less dispersed) information about the values of the output parameters (e.g. the tolerance interval narrowed almost by 1/2).

A decrease of the parameter dispersion (i. e. improvement of information) can be achieved either by better understanding of the pandemic mechanisms or by improved observation. The costs due to uncertainty can be considered as a measure of the value of additional information. This issue will be pursued in the future.

2.4. Variable Percentage of Vaccinated

Scenarios 1 a 2 represent the two opposite extremes of total costs, the number of deaths and their dispersions. This is due to the fact that under scenario 1 there is no vaccination whereas under scenario 2 all the population is pre-vaccinated, a vaccine being applied 3 times. To tie these extreme cases we have simulated scenarios that are compromises between scenarios 1 a 2 with pre-vaccinations of 20%, 40%, 60% or 80% of the population. The results are depicted in Figures 5 and 6 are summarized in Tables 6 a 7.

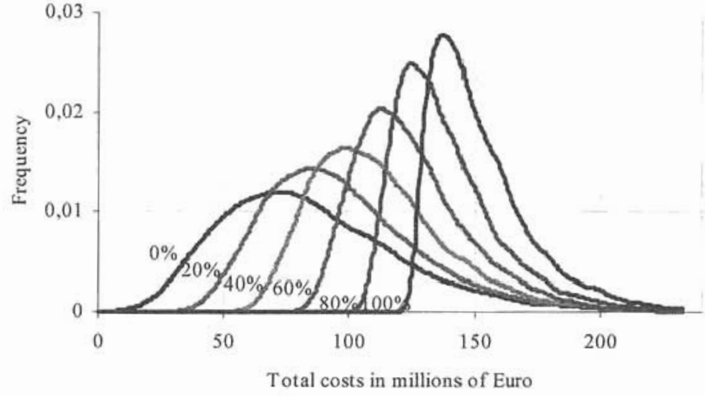
Table 6

Total Costs under Percentages of Pre-vaccinated

% of Pre-vaccinated	Mean	Median	Tolerance Interval	Interval Width
0	86.3	79.7	from 29.9 to 169.3	139.4
20	96.3	92.9	from 53.1 to 169.3	116.2
40	112.9	106.2	from 73 to 175.9	102.9
60	126.1	119.5	from 92.9 to 179.2	86.3
80	139.4	132.8	from 112.9 to 192.5	79.7
100	152.7	146.0	from 129.5 to 205.8	76.3

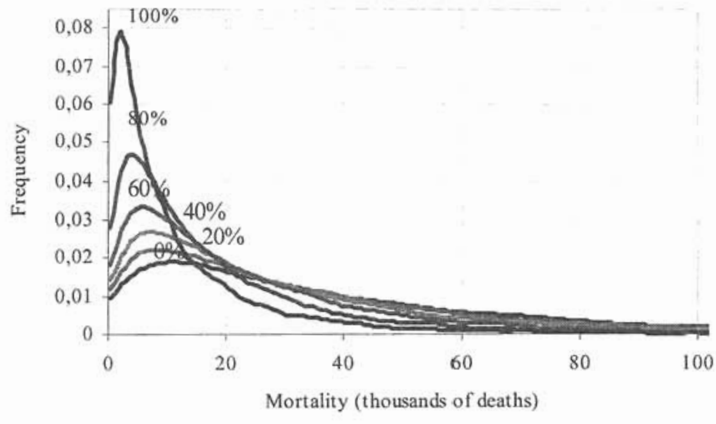
Note: Mean value, median, 95% tolerance interval and interval width in millions of Euro.
Source: Own results.

Figure 5
Total Costs under Varying Percentages of Vaccinated



Source: Own results.

Figure 6
Number of Deaths for Various Parameter Values



Source: Own results.

Table 7
Numbers of Deaths under Varying Percentages of Pre-vaccinated

% of Pre-vaccinated	Mean	Median	Tolerance Interval	Interval Width
0	40.9	28.7	from 1.7 to 153.3	151.6
20	34.3	24.3	from 1.5 to 123.5	122.0
40	28.8	20.1	from 1.2 to 103.4	102.2
60	23.5	16.3	from 1.0 to 85.1	84.1
80	17.8	11.6	from 0.6 to 69.7	69.1
100	12.3	6.7	from 0.2 to 57.6	57.4

Note: Mean value, median, 95% tolerance interval and interval width in thousands.

Source: Own results.

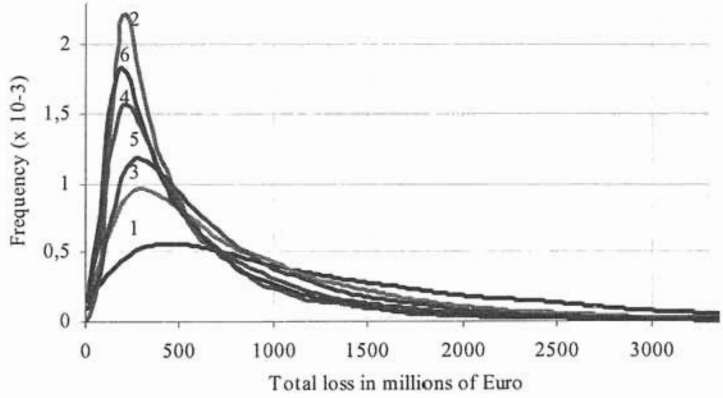
The graph labelled "0%" represents the non-intervention scenario 1. We see that an increase of the percentage of pre-vaccinated leads to an increase of total costs and a decrease of the number of deaths until the values of "100%", i.e., scenario 2 are reached. It is worth noting that an increase of the pre-vaccination percentage decreases the width of the estimated peaks, i.e. the dispersion of total costs and the number of deaths. As already mentioned, this is caused by the fact that by an increase of the percentage of pre-vaccinated individuals the probability of infection is decreased. This eliminates uncertainty of the costs and the number of deaths implied by the uncertainty of the number of infected.

2.5. Total Loss

Until now we have assessed the scenarios by the values of total costs and the number of deaths separately. These two criteria appear to be in conflict since by more vaccination total costs (consisting primarily from the vaccination costs) increase, while the number of deaths is considerably lower.

Now, we attempt to summarize these two indicators into one number to be called *total loss* consisting of total costs plus the number of deaths multiplied by the value of one life. The value of life is an extremely sensitive and questionable parameter. For illustration we have chosen the value 33,200 Euro (1,000,000 SKK). The estimated densities of total loss under particular scenarios are depicted in Figure 7 and summarized in Table 8.

Figure 7
Total Loss (= costs + loss due to lost lives)



Note: 1: no vaccination (so-called control); 2: whole population pre-vaccination (i.e. 2x pre-pandemic vaccination plus 1x pandemic); 3: 2x pandemic vaccination of 50% population; 4: 2x pre-pandemic vaccination of whole population; 5: pre-vaccination of 35% population plus 2x pandemic vaccination of 32.5% population; 6: 1x pre-pandemic plus 1x pandemic vaccination of whole population.

Source: Own results.

Table 8

Total Loss (= costs + value of lost lives).

Scenario	Mean	Median	Tolerance Interval	Interval Width
1	1,427.3	1,035.6	from 126.1 to 5198	5,072
2	561.0	371.8	from 142.7 to 2091	1,849
3	899.6	647.3	from 116.2 to 3090	2,974
4	663.9	441.5	from 112.9 to 2532	2,420
5	770.1	567.6	from 132.8 to 2589	2,390
6	594.2	385.0	from 103 to 2300	2,197

Note: Mean value, median, 95% tolerance interval and interval width in millions of Euro.

Source: Own results.

It appears that scenario 2 is best and scenario 1 worst. It should be noted, though, that this result is considerably affected by the parameter *value of life*. Should we choose a lower value of life, the optimal scenario could be different. In order to carry out an adequate optimization analysis it is unavoidable to make a more adequate estimate of vaccination costs including profit margins, taxes, costs of storing and carrying out vaccination. The vaccination cost then become a nonlinear function of its extent (i.e. he unit cost increases with vaccination extent) and includes and element of randomness due to the uncertainty of storing and acquirement.

2.6. The Costs per Life Saved and the Index of Effectiveness

The assessment of the vaccination scenarios by the total loss depends strongly on the subjectively chosen value of life. Alternatively, we can include mortality into consideration by the "costs per life saved" (see e.g. Gold et al., 1996). However, because the number of casualties is small compared to the size of the population, a certain normalization is needed. This is why we introduce an index of effectiveness. It relates the scenario under consideration to the non-interventional (control) scenario 1 by considering the increase of total costs and relative decrease of the number of deaths:

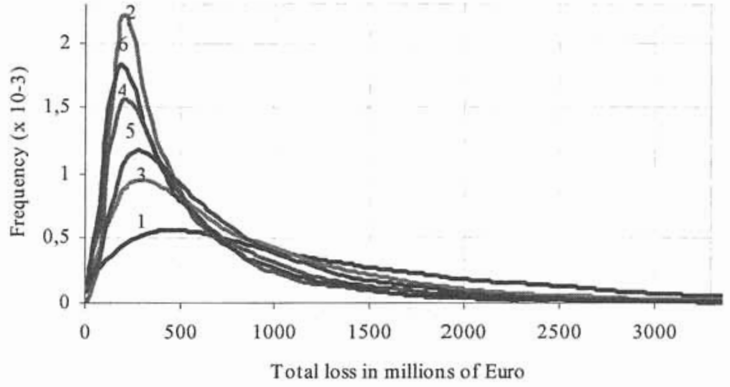
$$\frac{tc_i / tc_1}{(d_1 - d_i) / d_1}$$

Here tc_i and d_i stand for the total costs and number of deaths under the i-th scenario respectively. In order to compute the index we have carried out each of the 10 000 Monte Carlo simulation runs simultaneously for scenario i ($I = 2,...,6$) with the same random statistical parameters. Fitted densities of the simulated indices of effectiveness are depicted on Figure 8 and summarized in Table 9.

It is obvious that a decrease of the numerator and an increase of the denominator increases effectiveness. Hence, the smaller is the index of effectiveness, the more effective is the scenario. As one can see from Figure 8 and Table 9, scenario 6 (1x pre-pandemic plus 1x pandemic vaccination of whole population) appears to be the most effective one. It is rather surprising because this scenario did not appear to be optimal from the point of view of total costs including mortality.

Figure 8

Index of Effectiveness



Note: 2: whole population pre-vaccination (i.e. 2x pre-pandemic vaccination plus 1x pandemic); 3: 2x pandemic vaccination of 50% population; 4: 2x pre-pandemic vaccination of whole population; 5: pre-vaccination of 35% population plus 2x pandemic vaccination of 32.5% population; 6: 1x pre-pandemic plus 1x pandemic vaccination of whole population.

Source: Own results.

Table 9

Index of Effectiveness

Scenario	Mean	Median	Tolerance Interval	Interval Width
2	3.5	2.8	from 1.1 to 10.2	9.1
3	3.2	2.8	from 1.7 to 6.8	5.1
4	3.5	2.6	from 0.9 to 11.9	11.0
5	3.1	2.8	from 1.5 to 6.6	5.1
6	2.9	2.2	from 0.8 to 9.1	8.3

Source: Own results.

Conclusions

By random Monte Carlo simulations of pandemic influenza effects on the 5,400,000 inhabitants of Slovakia under several mitigation scenarios we have assessed their national impacts including economic costs and mortality losses. Simulation of individual cases allowed us to obtain the entire probabilistic distribution of the outcome variables. In particular, we have been able to obtain not only their expected values but also their dispersions.

We show that, although preventive measures mean extra social expenses, this is outweighed by the reduction of losses due to mortality. A direct assessment of the mortality losses involves a subjective element – the value of life. In order to remedy this difficulty we introduce an index measuring the costs of lives saved by a particular intervention measure. Rather unexpectedly, this index indicates the scenario of one pre-pandemic and one pandemic vaccination as the most effective.

It is worthwhile to observe that dispersions representing uncertainty are the lowest under the most expensive scenario of twice pre-pandemic and once pandemic vaccination of the total population. Since uncertainty represents additional costs, the dispersions should be taken into account when comparing different mitigation scenarios as well. Expressing this circumstance in economic terms needs an assessment of the uncertainty costs which is an interesting challenge for further research.

References

BERAN, J. – HAVLÍK, J. (2005): Chřipka – klinický obraz, prevence, léčba. Praha: Maxdorf, pp. 10 – 17.

DOYLE, A. – BONMARIN, I. – LÉVY-BRUHL, D. – LE STRAT, Y. – DESENCLOS, J. C. (2006): Infuenza Pandemic Preparedness in France: Modelling the Impact of Interventions. Journal of Epidemiol Community Health, *60*, pp. 399 – 404.

FERGUSON, N. M. et al. (2006): Strategies for Mitigating an Influenza Pandemic. Nature, *442*, pp. 448 – 452.

FRASER, C. – RILEY, S. – ANDERSON, R. M. – FERGUSON, N. M. (2004): Factors that Make an Infectious Disease Outbreak Controllable. PNAS, *101*, pp. 6146 – 6151.

GERMANN, T. C. – KADAU, K. – LONGINI, I. M. – MACKEN, C. A. (2006): Mitigation Strategies for Pandemic Influenza in the United States. PNAS, *103*, pp. 5935 – 5940.

GOLD, M. R. et al. (1996): Cost-Effectiveness in Health and Medicine. New York: Oxford University Press.

HAK, E. et al. (2006): Modelling the Health – Economic Impact of the Next Influenza Pandemic in the Netherlands. Vaccine, *24*, pp. 6756 – 6760.

LAZZARI, S. – STŐHR, K. (2004): Avian Influenza and Influenza Pandemics. Bulletin WHO, *82*, pp. 242 – 243.

LEROUX, I. R. et al. (2007): Antigen Sparing and Cross- Reactive Immunity with an Adjuvanted rH5N1 Prototype Pandemic Vaccine a Randomized Controlled Trial. Lancet, *370*, pp. 580 – 589.

LONGINI, I. M. et al. (2005): Containing Pandemic Influenza at the Source. Science, *309*, pp. 1083 – 1087.

MELTZER, M. – COX, N. – FUKUDA, K. (1999): The Economic Impact of Pandemic Influenza in the United Sates: Priorities for Intervention. Emerg. Infect. Dis., *5*, pp. 659 – 671.

Pandemic Plan of Czech Republic 2006. Available at: <www.mzcr.cz/Pages/258-pandemicky-plan-ceske-republiky.html>.

TAUBENBERGER, J. K. – MORENS, D. M. (2006): 1918 Influenza: the Mother of All Pandemics. Emerg. Infect. Dis., *12*, pp. 15 – 22.

VAN GENUGTEN, M. L. – HEIJNEN, M. L. – JAGER J. C. (2003): Pandemic Influenza and Healthcare Demand in the Netherlands: Scenario Analysis. Emerg. Infect. Dis., *9*, pp. 531 – 538.

WHO (2008a): Cumulative Number of Confirmed Human Cases of Avian Influenza A (H5N1) Reported to WHO. Available at: <www.who.int/csr/disease/avian_influenza/country/cases_table_2008_09_10/en>.

WHO (2008b): Writing Committee of the Second World Health Organization Consultation on Clinical Aspects of Human Infection with Avian Influenza A (H5N1) Virus: Update on Avian Influenza A (H5N1) Virus Infection in Humans. New England Journal of Medicine, *358*, pp. 261 – 273.

III.9. SBA WATER by GEO-BENE Consortium Partners

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Food consumption patterns and their effect on water requirement in China

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Abstract. It is widely recognized that food consumption patterns significantly impact water requirements. The aim of this paper is to quantify how food consumption patterns influence water requirements in China. The findings show that per capita water requirement for food (CWRF) has increased from 255 m^3 $cap^{-1}y^{-1}$ in 1961 to 860 m^3 cap^{-1} y^{-1} in 2003, largely due to an increase in the consumption of animal products in recent decades. Although steadily increasing, the CWRF of China is still much lower than that of many developed countries. The total water requirement for food (TWRF) has been determined as 1127 km^3 y^{-1} in 2003. Three scenarios are proposed to project future TWRF, representing low, medium, and high levels of modernization (S1, S2, and S3, respectively). Analysis of these three scenarios indicates that TWRF will likely continue to increase in the next three decades. An additional amount of water ranging between 407 and 515 km^3 y^{-1}will be required in 2030 compared to the TWRF in 2003. This will undoubtedly put high pressure on China's already scarce water resources. We conclude that the effect of the food consumption patterns on China's water resources is substantial both in the recent past and in the near future. China will need to strengthen "green water" management and to take advantage of "virtual water" import to meet the additional TWRF.

1 Introduction

Besides population growth and externalities of uncontrolled economic growth, water scarcity is more and more recognized as a major threat to sustainable development (Koudstaal et al., 1992; Postel et al., 1996; Vörösmarty et al., 2000; Oki and Kanae, 2006). While water stress is often a direct result of population growth and economic development, this paper shows that changing consumption patterns may potentially become the main cause of water scarcity. Currently, approximately one third of the world's population lives in countries suffering water stress (Oki and Kanae, 2006). Many authors have projected that a large share of the world's population – up to two-thirds – will be affected by water scarcity over the next decades (Shiklomanov, 1991; Raskin et al., 1997; Seckler et al., 1998; Alcamo et al., 2000; Vörösmarty et al., 2000; Oki and Kanae, 2006).

The problem of water scarcity, in essence, originates from insufficient water for the production of food. Almost 90% of an individual's water requirement is needed for food production (Savenije, 2000). As a general rule, about 1–2 m^3 of water is required to produce 1 kg of cereal (Allan, 1998;Yang et al., 2003). More water is needed to produce one kilogram of meat. For example, it takes about 13.5 m^3 of water to produce 1 kg of beef in California (Rijsberman, 2006). This means that the water requirement for consuming 1 kg of beef is equivalent to almost three-fourths of the recommended human's annual basic water requirement for drinking, human hygiene, sanitation, and modest household needs for preparing food (i.e. 50 liters cap^{-1} day^{-1}, or 18 m^3 cap^{-1} y^{-1}) (Gleick, 1996).

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A human being "eats" thousands of liters of water each day; however, the exact amount largely depends on food consumption patterns. Renault and Wallender (2000) estimated that a typical American diet requires twice as much water as a vegetarian diet with the same nutritional intake. Unraveling the effects of various food consumption patterns on water requirement help formulate appropriate water and food policies.

In water resources management it is important to make a distinction between "blue" and "green" water resources (Falkenmark, 2003). Green water is essentially the rainfall that (after infiltration in the unsaturated zone) is directly consumed by plants to produce biomass. Blue water is the water that occurs in water bodies and groundwater, which can be used for irrigation. Most of the global food production relies on "green" water (rainfed agriculture). Liu (2007) computed that 81% of the global consumptive water use for crop production is green water and that the world water trade in the form of agricultural products ("virtual" water trade as defined by Allen, 1998) relies for 90% on green water. Although most of the global concerns on water scarcity relate to blue water, it is imperative to study water scarcity in the context of blue and green water interaction, and to consider the partitioning of rainfall into blue and green water, including their spatial and temporal patterns.

This paper aims to quantitatively examine the effects of food consumption patterns on water requirements in China. However, the conclusions of this study range beyond the China case. The developments we observe in China may be of gigantic proportions compared to other countries, but similar developments can be expected in other developing countries and the world at large. The changing food consumption patterns will drastically affect the partitioning between green and blue water and influence the virtual water trade worldwide.

China has been selected for three reasons. First, with a population of about 1.3 billion, China feeds the largest number of consumers in the world; second, in the major food production area, or the North China Plain, blue water resources are only $500\,m^3\,cap^{-1}\,y^{-1}$(MWR, 2005). The constraint of water scarcity on food production has led to growing concerns regarding China's food production, food security, and their impacts on the global food market (Liu et al., 2007c); third, China has experienced fast economic growth with an annual GDP growth rate of 8% over the past two decades; the highest rate in recent world history. Consumers' income has risen substantially, resulting in a rapid dietary change towards more meat consumption (FAO, 2006; Du et al., 2004). The shift in food consumption patterns will undoubtedly have profound effects on water requirements, but in-depth analysis on these effects is rarely found in literature.

2 Concept, method and data sources

2.1 Food requirements at three scale levels

In this paper, food requirements are classified into three levels of scale: the basic level, the subsistence level and the cultural level, as suggested by Gerbens-Leenes and Nonhebel (2002). At the basic level, food requirements are only sufficient to prevent starvation, but one may suffer from malnutrition in the long run because many essential nutrients are lacking. At this level, the main purpose of food intake is to provide enough energy for basic survival and physical activity. At the subsistence level, food requirements are based on a selected number of nutrient-dense foods recommended that enable one to lead a healthy life over an entire life span. At the cultural level, food requirements correspond to the actual consumption pattern, which is embedded in different types and quantities of food and their combination in different dishes or meals. In order to analyze food requirements at the cultural level, food items have been grouped in six categories:

1. cereals and starchy roots (including rice, wheat, maize, other cereals, potatoes and other starchy roots);
2. sugar and sweeteners;
3. oil crops and vegetable oils;
4. vegetables and fruits;
5. alcoholic beverages; and
6. animal products (including beef, pork, poultry, mutton and goat, fish and seafood, eggs, milk, animal fats).

In 2003, these foods accounted for 98% of both the total food consumption in weight and the total calorie intake (FAO, 2006).

2.2 Virtual water content

The virtual water content (VWC) can be defined as the volume of water used to produce a unit of product at the place where the product is actually produced, or alternatively as the volume of water that would have been required to produce the product in the place where the product is consumed (Chapagain and Hoekstra, 2004). In China, food consumption mainly originates from domestic food production. Food imports are marginal compared to domestic production. For example, in 2003, the imports of cereals and meat were only amounted to about 3% of the domestic production in weight (FAO, 2006). Due to the small share of food import, the VWC values are determined on the basis of China's specific production conditions. Hence, the first definition of VWC is used in this study. Strictly speaking, the first definition does not imply "virtual" water trade in the literal sense. Hoekstra and Chapagain (2007) used the term of "water footprint" for

Table 1. Virtual water content and energy water productivity for mostly consumed food items.

Food Items		Virtual water content ($m^3 kg^{-1}$)	Energy content ($kcal\ kg^{-1}$)	Energy water productivity ($kcal\ m^{-3}$)
Cereals and Roots				
Rice		1.31	3625	2770
Wheat		0.98	2633	2701
Maize		0.84	2872	3403
Other cereals	†	1.24	2709	2185
Potatoes and other starchy roots	‡	0.23	699	3107
Sugar and Sweeteners	§	1.02	3481	3423
Oil crops and Vegetable oils				
Soybeans and other oil crops	||	3.20	3314	1035
Vegetable oils	¶	5.08	8720	1715
Vegetables and Fruits				
Vegetables	#	0.19	188	995
Fruits	††	0.50	413	834
Animal products				
Beef		12.56	2021	161
Pork		4.46	3500	785
Poultry		2.39	1708	715
Mutton and goat meat	‡‡	4.50	2005	446
Fish and sea food		5.00	497	99
Eggs		3.55	1455	410
Milk		1.00	670	670
Animal fats		4.00	7080	1770
Alcoholic beverages§§		0.18	490	2768

† based on data for sorghum
‡ based on data for potatoes
§ based on data for refined sugars
|| based on data for soybeans
¶ based on data for soybean oil
# based on data for tomatoes
†† based on data for apples
‡‡ based on average data for goat meat and sheep meat
§§ based on data for beer
Sources: virtual water content (VWC) of cereals, soybean, vegetables and fruits from Liu et al. (2007c); VWC of fish and seafood from Zimmer and Renault (2003); VWC of other food items from Chapagain and Hoekstra (2004); Energy content of all food items from FAO (2006).

the first meaning. Hence, the term of VWC in this paper is equivalent to the term of "water footprint" in Hoekstra and Chapagain (2007).

VWC of a crop is generally calculated by dividing consumptive water use (or the sum of crop transpiration and soil evaporation during the crop growing period, in $m^3\ ha^{-1}$) with crop yield (in $kg\ ha^{-1}$) (Liu et al., 2007b) .VWC of an animal at the end of its life span is generally calculated as the total volume of water that was used to grow and process its feed, to provide its drinking water, and to clean its housing and the like (Chapagain and Hoekstra, 2004). Table 1 shows the VWC values for the main food items in China. All these values are obtained from literature except for the VWC of pork. Chapagain and Hoekstra (2004) calculate a VWC value of 2.21 $m^3\ kg^{-1}$ for pork. This value is likely underestimated. In China, to produce 1 kg of pork, about 4.6 kg of maize and 1.2 kg of rough forage are required (Zhang, 2003). The VWC of maize is 0.84 $m^3\ kg^{-1}$ (Table 1), and the VWC of forage is about 0.5 $m^3\ kg^{-1}$ (Zhang, 2003). Hence, the VWC of pork is estimated to be 4.46 $m^3\ kg^{-1}$, which is almost double the value from Chapagain and Hoekstra (2004).

Generally, animal products, oil crops and vegetable oils have relatively high VWC values compared to other food items. Particularly, beef has the highest VWC of 12.6 $m^3\ kg^{-1}$ of all food items. In contrast, vegetables and fruits have the lowest VWC. The VWC values of cereals are between 0.84 and 1.31 $m^3\ kg^{-1}$.

2.3 Energy water productivity

Energy water productivity is defined as the energy produced by one unit of water, and is calculated by dividing the energy content of a food crop by its VWC. The data on energy content have been taken from the FAO Food Balance Sheets for China's food consumption in 2003 (FAO, 2006). Cereals and starchy roots have the highest energy water productivity, ranging between 2185 $kcal\ m^{-3}$ and 3403 $kcal\ m^{-3}$

Table 2. Food consumption patterns of China over time.

Food Items	Per capita annual food consumption (kg cap^{-1}yr^{-1})									
	1961	1965	1970	1975	1980	1985	1990	1995	2000	2003
Cereals and Starchy roots										
Rice	50	72	78	80	84	98	93	91	88	79
Wheat	22	34	34	43	61	78	81	79	74	61
Maize	21	18	20	21	26	23	25	19	17	15
Other cereals	26	25	23	19	15	12	8	5	3	3
Potatoes and other starchy roots	112	105	118	109	91	66	59	59	75	74
Sugar and Sweeteners	2	3	3	3	5	7	8	7	7	8
Oil crops and Vegetable oils										
Soybeans and other oil crops	5	5	6	5	5	6	6	7	8	7
Vegetable oils	1	2	2	2	3	4	6	7	8	11
Vegetables and Fruits										
Vegetables	79	57	44	47	49	79	99	148	225	270
Fruits	4	5	5	6	7	11	17	32	43	50
Animal products										
Beef	0.1	0.3	0.3	0.3	0.4	0.5	1	3	4	5
Pork	2	7	7	8	12	16	20	27	33	35
Poultry	1	1	1	1	2	2	3	7	11	11
Mutton and goat meat	0	0	0	0	0	1	1	1	2	3
Fish and sea food	5	5	5	6	5	7	11	21	26	25
Eggs	2	2	2	2	3	5	6	13	16	18
Milk	2	2	2	2	3	5	6	8	10	17
Animal fats	0	1	1	1	1	1	1	2	2	2
Alcoholic beverages	1	2	2	3	5	8	13	23	24	27

Sources: FAO (2006)

(Table 1). Animal products generally have much lower energy water productivity than plant products. For instance, beef needs 17 times more water than wheat to supply the same amounts of energy. If the average energy requirement of 2250 kcal cap^{-1} day^{-1} is covered by wheat, then 0.8 m^3 cap^{-1} day^{-1} of water is required. However, if this amount of energy is covered by beef 14 m^3 cap^{-1} day^{-1} is needed.

2.4 Historical food consumption patterns

Chinese diets have shifted towards animal products, particularly meat. Meat used to be luxury food in China, and its consumption remained at low levels prior to 1980. However, meat consumption has risen rapidly, by a factor of 3.7 from 1980 to 2003. The large increase in meat consumption is mainly due to the rapid increase in per capita income, urbanization, and market expansion (Hsu et al., 2002; Huang et al., 1999). In the past four decades, the consumption of rice and wheat increased gradually until it peaked in the late 1990s. Since then, cereal consumption has dropped. The consumption of maize changed little over time, with only a slight decline in recent years. The consumption of starchy roots steadily declined until 1995, and then bounced back in the early 2000s. Another remarkable change was the significant increase in vegetable and fruit consumption. On average, the consumption of fruits and vegetables reached 320 kg cap^{-1} y^{-1} in 2003, which is a fourfold increase compared to that in 1961, and is now the most abundantly eaten food type in weight. The consumption of sugar and sweeteners, oil crops and vegetable oils and alcoholic beverages is also increasing. The historical food consumption of various food items over time is presented in Table 2.

2.5 Per capita water requirement for food

Per capita water requirement for food (CWRF) is defined as the amount of water used to produce certain food requirements on a per capita basis. The CWRF is calculated by multiplying the food requirements per food item by the VWC of the corresponding food item and then summing the results for the food categories. Three levels of CWRF (basic CWRF, subsistence CWRF, and cultural CWRF) have been estimated based on the three scale levels of food requirements. The basic CWRF is determined based on two considerations. First, the caloric energy requirements are hypothesized to be met only by the consumption of wheat (Gerbens-Leenes and Nonhebel, 2002); second, according to the Chinese Nutrition Society (CNS), at least 2400 and 2100 kcal cap^{-1} day^{-1} of energy is required for male and female Chinese adults, respectively, to carry out light physical activities under healthy living conditions. Thus, the average of 2250 kcal cap^{-1} day^{-1} has been used as the recommended energy intake at the basic level. It may be argued that, while wheat is a staple food in the Northern part of China, rice is a more consumed food in the Southern part. However, the energy water productivity of wheat is almost identical to that of rice (Table 1). Hence, the basic CWRF calculated

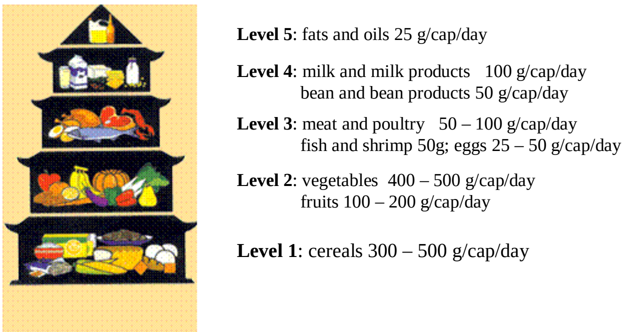

Fig. 1. Chinese food guide pagoda from the Chinese Nutrition Society.

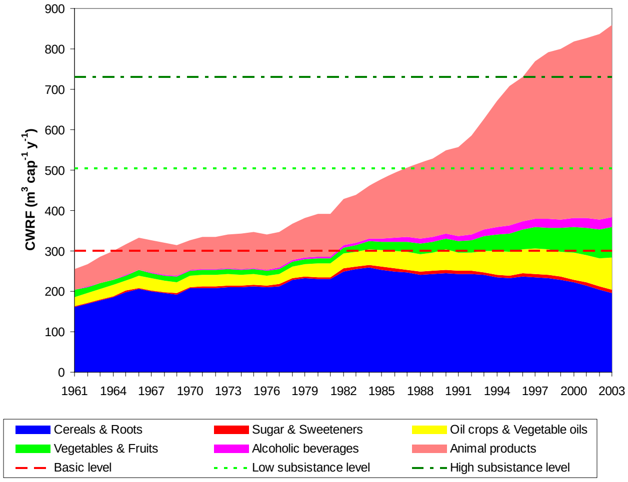

Fig. 2. The per capita water requirement for food (CWRF) at the basic, subsistence and cultural levels. CWRF is calculated based on VWC values of various food items for the year around 2000.

with only wheat consumption is justified here. The calculation of subsistence CWRF is based on the recommended daily amounts of food intake from the food guide pagoda of the CNS (http://www.cnsoc.org). The food guide pagoda is available in Fig. 1. According to CNS, 100 g of milk and milk products are equivalent to 200 g of fresh milk, and 50 g bean and bean products are equivalent to 40 g of soybean. These equivalences are used in the calculation of subsistence CWRF. Further, the consumption ratio of different cereals (in weight) and meat has been assumed identical to the cereal consumption pattern in 2003. The cultural CWRF is calculated based on actual food consumption patterns. Annual consumption of various food items over 1961–2003 is obtained from FAOSTAT (FAO, 2006).

2.6 Total water requirement for food

Total water requirement for food (TWRF) is the total amount of water consumed to produce certain food requirements for all the individuals in a country. It is calculated for China by multiplying CWRF by the population. Historical population data have been obtained from FAO (2006) for the period of 1961–2003. TWRF at the basic and subsistence levels have not been calculated, because these two levels are purely hypothetical situations which do not provide any information on the current and future water requirement situation.

3 Water requirement for food

3.1 Historical CWRF

Basic CWRF is estimated to lie around 300 $m^3\,cap^{-1}\,y^{-1}$. Subsistence CWRF ranges from 505 to 730 $m^3\,cap^{-1}\,y^{-1}$. These two numbers correspond to low and high subsistence levels respectively. The low subsistence level is determined by using the lower limits of food consumption for various food groups in Fig. 1, while the high subsistence level is determined by using the upper limits. CWRF at the high subsistence level is more than double the basic CWRF. Figure 2 presents the estimated cultural CWRF from 1961 to 2003, indicating the basic and subsistence CWRF levels.

The cultural CWRF in the early 1960s was lower than the basic CWRF (Fig. 2). The year 1961 is the last year of the so-called "three bad years", which contained a series of calamities that resulted in the deaths of tens of millions directly caused by starvation. In 1961, the Chinese government started to introduce a series of new economic policies known as "readjustment, consolidation, filling-out, and raising standards" to boost agricultural production. Consequently, cereal consumption (particularly wheat and rice consumption) rose steadily, which led to an increase in CWRF from 1961 to 1965. Afterwards, the Cultural Revolution, 1966–1976, which involved devastating social turmoil, had adverse effects on agricultural production. Over this period, cultural CWRF remained close to the basic level. After the Cultural Revolution, China abandoned collective agriculture and in 1978 assigned most agricultural land to families under the household responsibility system. The adoption of this system contributed to technological changes, which played an important role in driving productivity, particularly in the 1980s (Liu and Yin, 2004). Between 1978 and 1984, the rise of cultural CWRF was largely due to higher consumption of cereals and starchy roots and animal products. After 1984, consumption of cereals and starchy roots showed a slight decline. The increase in cultural CWRF was mainly caused by higher consumption of animal products, oil crops and vegetable oils, and vegetables and fruits. Cultural CWRF reached low subsistence CWRF in the late 1980s, and then arrived at high subsistence CWRF in the middle 1990s. In 2003, the cultural CWRF reached 860 $m^3\,cap^{-1}\,y^{-1}$, which is about 18% higher than the CWRF at the high subsistence level. This is mainly due to meat and fish consumption being

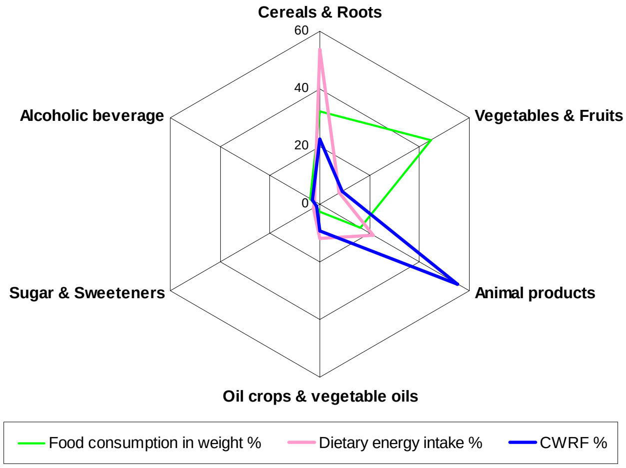

Fig. 3. Sources of food consumption in weight, dietary energy intake and CWRF in 2003. All are presented as the percentage of the total.

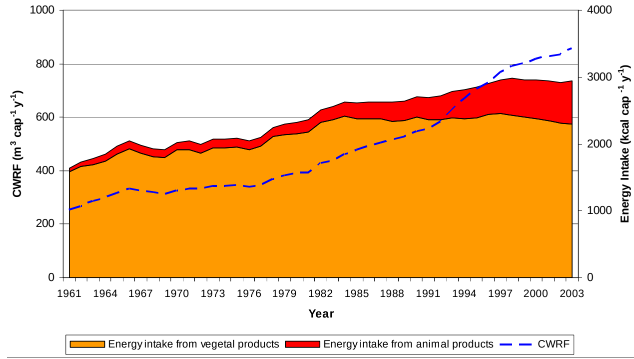

Fig. 4. Relation between energy intake and per capita water requirement for food (CWRF) at the cultural level over 1961–2003.

higher than the CNS recommended amount by about 50%. The contribution of animal products to CWRF has increased from 20% to 55% from 1961 to 2003. The contribution of cereals and starchy roots decreased from 63% to 23% during the same time span. Water requirement for the consumption of both vegetables and fruits and oil crops and vegetable oils steadily increased over time, contributing to 18% of CWRF in 2003.

Per capita water requirement for animal products has increased by 33% since 1996. In contrast, water requirement for the consumption of non-animal products almost leveled off over this period. Increasing water requirement for vegetables and fruits and oil crops and vegetable oils is almost compensated by decreasing water requirement for cereals and starchy roots.

Water requirements for the consumption of specific food items or categories depend not only on food consumption in weight but also on the VWC of these foods. For instance, even though animal products accounted for only 16% of total food consumption in weight in 2003, their production required 55% of the cultural CWRF (Fig. 3). In contrast, vegetables and fruits accounted for 44% of the total food consumption in weight, but their consumption only resulted in about 9% of CWRF. The VWC of animal products generally has much higher values than that of vegetables and fruits, as shown in Table 1. As a result, some food items take a disproportional share of the water requirements. Similarly, some food groups have a disproportional share of the dietary energy intake and cultural CWRF (Fig. 3). In this regard, the energy water productivity plays a key role.

It should be pointed out that the VWC values used in this study (Table 1) are based on estimations for the years around 2000. VWC values fluctuate. For example, Xu and Zhao (2001) report that VWC of rice decreased from $4.3\,m^3\,kg^{-1}$ in 1949 to $1.1\,m^3\,kg^{-1}$ in 1996 in Fengqiu County in China. This decrease in VWC is mainly caused by technological innovations including the establishment of water conservation facilities, better soil management, extension of new crop varieties, and a continuous increase in fertilizer application (Xu and Zhao, 2001). Annual VWC values of various food items in China are, unfortunately, rarely available. However, this should not influence the presented analysis, as its main objective is to demonstrate the effect of consumption patterns alone on CWRF, while holding all other variables constant. Therefore, the influence of technological changes has not been included. However, it will be taken into account in the scenario analysis of the future TWRF.

3.2 Historical cultural CWRF and energy intake

Cultural CWRF and energy intake has changed at almost equal annual growth rates between 1961 and 1984 (see Fig. 4). They both increased at a rate of 5% y^{-1} from 1961 to 1965, remained almost zero from 1966 to 1976, and increased again at a rate of about 4% y^{-1} from 1977 to 1984. Over the period 1961–1984, consumption of animal products hardly varied; and energy intake from animal products remained relatively constant. The variation in total energy intake was mainly caused by changes in the consumption of cereal crops and starchy roots (FAO, 2006). Cereals and starchy roots have similar energy water productivity, resulting in the similar increase rates of cultural CWRF and energy intake.

From 1985 to 1997, however, the CWRF increased much faster than total energy intake. Growth rates of CWRF and total energy intake were 5% y^{-1} and 1% y^{-1}, respectively. The main reason for the faster growth of CWRF was the increase in the consumption of food items with low energy water productivity (e.g. animal products) and less consumption of the food items with high energy water productivity (e.g. starchy roots). Although total energy intake from non-animal products only increased slightly, consumption of various plant products changed. Consumption of cereals and starchy roots declined, while consumption of vegetables and fruits increased significantly, thus causing a further growth of CWRF.

Since 1997, energy intake has slightly declined. The decrease in energy intake from cereals and starchy roots outweighed the increase in energy intake from animal products. Lower energy water productivity of animal products led to a further increase in CWRF.

3.3 Comparison with other regions

In order to assess regional variation, cultural CWRF values have been estimated in different regions based on the food consumption patterns in 2003 and the VWC values shown in Table 1. The regions analyzed are the European Union (the 15 member countries as a whole prior to the accession of the candidate countries on 1 May 2004, termed as EU15 here), USA, Japan, South Korea, developing countries as a whole (Developing), developed countries as a whole (Developed), and the world at large (World). Developed and developing countries have been distinguished according to the classification by the Food and Agriculture Organization of the United Nations (FAO, 2006).

Cultural CWRF values vary significantly among regions (Fig. 5). The largest value is for the USA (1820 m^3 cap^{-1} y^{-1}), and the smallest for the developing countries (685 m^3 cap^{-1} y^{-1}). The CWRF of China is slightly higher than that of the world average, but is much lower than that of developed countries, particularly EU15 and the USA (Fig. 5). Two other Asian countries, Japan and South Korea, have a cultural CWRF value of 26% and 30% higher than China, respectively. The relatively low CWRF of China is mainly due to lower consumption of animal products. For example, in the USA, the consumption of animal products corresponds to almost 1227 m^3 cap^{-1} y^{-1} of water. This volume alone is much larger than the CWRF of China. Additionally, developed countries also consume more sugar and sweeteners and alcoholic beverages than China. Water requirements for the consumption of cereals and starchy roots hardly vary among regions.

In the near future, dietary changes in China, directed towards higher consumption of animal products, will continue to bear on water requirements. If China shifts towards the American level of animal product consumption, the cultural CWRF will more than double the present level. Similarly, if consumption patterns in developing countries would shift towards the affluent diets of western countries, the CWRF values would rise up to a three fold increase. Such a change in food consumption pattern would play a much greater role in increasing water requirements than population growth.

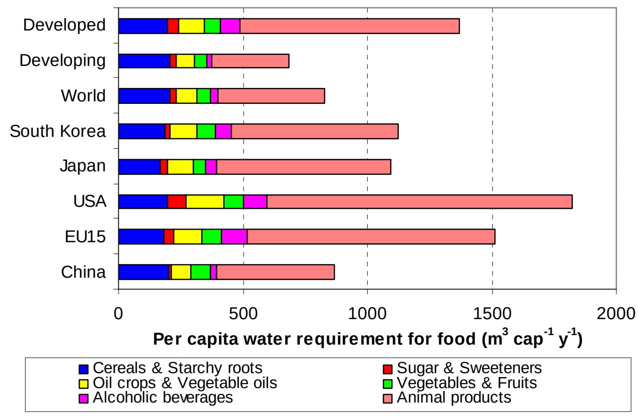

Fig. 5. Per capita water requirement for food (CWRF) at the cultural level in 2003 in different regions. CWRF in all regions is estimated with VWC of individual food items determined on the basis of China's specific production conditions.

3.4 CWRF and TWRF in the future

The TWRF is estimated at 1127 km^3 y^{-1} in China in 2003. The future levels of CWRF and TWRF largely depend on food consumption patterns and future population. In addition, technological changes will also have a profound impact on both CWRF and TWRF via their influence on VWC. Accurate estimation of future food consumption patterns is very difficult. Several studies estimated future meat consumption, such as 30–50 kg cap^{-1} y^{-1} for 2025 (Heilig, 1999), 51.3 kg cap^{-1} y^{-1} for 2020 (World Bank, 1997), and 63 kg cap^{-1} y^{-1} for 2020 (Christopher et al., 1998). In 2003, meat consumption reached 55 kg cap^{-1} y^{-1} (FAO, 2006) demonstrating that the first two studies already underestimated present consumption. Hence, future CWRF estimation based on these projections would lead to large errors. In this paper, future CWRF values have been determined based on the general trend of historical food consumption patterns of individual food items. The baseline annual growth rates of food consumption of individual food items are calculated based on the food consumption pattern over 1998–2003. Future growth rates are analyzed under three scenarios based on the baseline annual growth rates.

Technological changes may affect VWC values. According to Liu et al. (2007b), crop water productivity (CWP) for different crops, or the inverse of VWC, has a strong linear relation with crop yield. The linear relation exists even when setting the intercept at zero (r^2=0.77). This relation allows fixing the annual growth rate of the CWP at the annual growth rate of the crop yield. In this way, we can estimate the future VWC if the effects of technological change on crop yield are known. The average annual growth rates of crop yield for individual crops over 1998–2003 are set as baseline annual growth rates. To reduce the annual variation 3-year averages are used in the calculation. For example, the

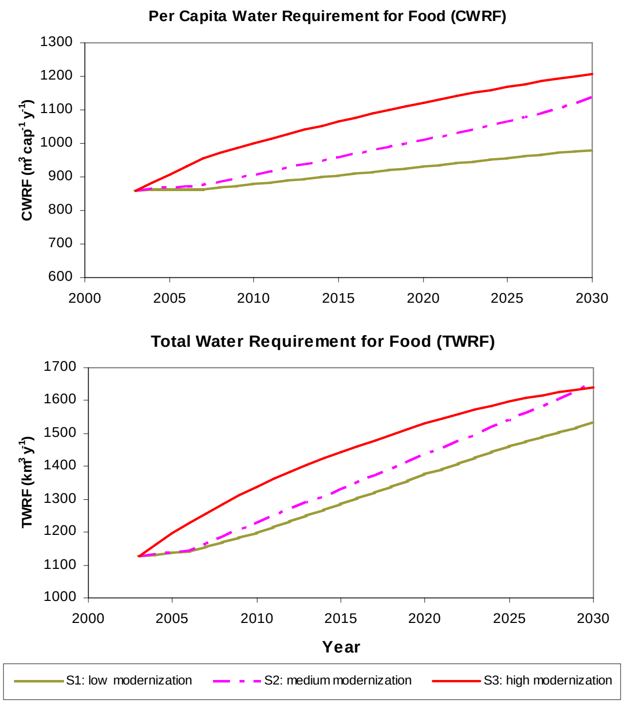

Fig. 6. Per capita water requirement for food (CWRF) and total water requirement for food (TWRF) in 2003–2030 under three scenarios.

average yield between 2002 and 2004 is treated as the yield in 2003. Future annual growth rates of crop yield are assumed in three scenarios based on the baseline growth rates. It needs to be pointed out that the linear relation between CWP and crop yield may not always hold true, for example, when drought tolerant crop varieties are introduced (e.g. replacement of paddy rice by aerobic rice). However, the relation provides a simple and often reliable way to project CWP in the future.

The relation between technological changes and VWC of animal products is more complex. Some animals such as pigs, goats, and chicken largely rely on grain feed (mainly maize), while animals such as cattle and cows mainly feed on pasture land. For example, about 80% of the VWC of pork is related to maize, and the remaining 20% is related to rough forage (Zhang, 2003). In contrast, only 3% of VWC of beef is related to grain, while the remaining is related to green grass (Zhang, 2003). Crop yields of rough forage and grasses over time are commonly not reported in China. It is expected that the yields of rough forage and grasses are mainly affected by local climate and soil conditions, and that they are not significantly influenced by technological innovations. As a result, we assume that the annual growth rates of the VWC of pork, poultry, mutton and goat meat, eggs, and animal fats (mainly fats of pigs are consumed in China) are equal to the annual growth rate of the VWC of maize. The VWC values of all other animal products are assumed constants over time.

The projection of China's future population has been taken from the 2006 revision of *World Population Prospects* (United Nation, 2006). Here we use the period prior to 2030 for scenario analysis. According to the medium variant of the UN's projection, China's population may reach its maximum in 2030 after which it is expected to decline. Thus, in the nearest future China will face its greatest challenge in meeting domestic food demand. To analyze the TWRF in the period of 2004–2030, three scenarios have been developed.

Low modernization scenario (S1)

The annual growth rates of food consumption of individual food items slow down to 50% of the baseline annual growth rates of food consumption. Technological innovations increase yields of individual crops, but the annual growth rates of crop yield are only 50% of the baseline annual growth rates for the corresponding food items. Population growth follows the high variant of the UN population projection.

Medium modernization scenario (S2)

The annual growth rates of food consumption of individual food items remain the same as the baseline annual growth rates. The baseline annual growth rate of crop yield of each food item will continue over the next three decades due to technological innovations. Population growth follows the medium variant of the UN population projection.

High modernization scenario (S3)

The annual growth rates of food consumption of individual food items are 50% higher than the baseline annual growth rates. Technological innovation increases yield, and the annual growth rates of crop yield of individual crops are 50% higher than the baseline annual growth rates. Population growth follows the low variant of the UN population projection.

The results of future CWRF and TWRF scenarios S1–S3 are presented in Fig. 6. Under S1, the shift in food consumption patterns alone will result in 22% more TWRF in 2030 compared to that in 2003, while population growth alone will lead to 19% more TWRF. Both factors combined increase the TWRF by 45% over 2003–2030. Technological changes decrease the VWC by about 6% for all the food items as a whole. As a result, TWRF reaches 1534 $km^3\,y^{-1}$ in 2030, about 36% higher than in 2003. Without considering technological changes, CWRF will arrive at 1043 $m^3\,cap^{-1}\,y^{-1}$ in 2030, slightly lower than the CWRF in Japan at current level (in 2003). After taking technological changes into account, CWRF will arrive at 981 $m^3\,cap^{-1}\,y^{-1}$ in 2030.

Under S2, the shift in food consumption and population growth will lead to 46% and 11% increase in 2030 compared to 2003, respectively. Both factors combined will increase the TWRF by 62%. Technological innovation alone will decrease the VWC by 9% for all the food items as a whole. As a result, TWRF arrives at 1658 $km^3 y^{-1}$ in 2030, about 47% higher than in 2003. Without considering technological changes, CWRF will arrive at 1249 $m^3 cap^{-1} y^{-1}$ in 2030, about 10% higher than the CWRF in South Korea at current level (in 2003). After taking technological changes into account, CWRF will be 1137 $m^3 cap^{-1} y^{-1}$.

Under S3, the shift in food consumption patterns and population growth will result in 56% and 4% increase compared to 2003, respectively, whereas both factors combined increase the TWRF by 62%. Technological innovation decreases the VWC by 10% for all the food items as a whole. As a result, TWRF arrives at 1641 $km^3 y^{-1}$ in 2030, about 46% higher than in 2003. Without considering technological changes, CWRF will arrive at 1342 $m^3 cap^{-1} y^{-1}$ in 2030, almost reaching the average CWRF in developed countries at current level (in 2003). After taking technological changes into account, CWRF will be 1208 $m^3 cap^{-1} y^{-1}$.

Whatever scenario is used, the TWRF will continue to increase in the next three decades. An additional amount of water ranging between 407 and 515 $km^3 y^{-1}$ will be required compared to the TWRF in 2003. This is a substantial increase, which amounts to 182–230% of current consumptive irrigation water use (MWR, 2005). The analysis also suggests that the shift in food consumption pattern will contribute more to the growth of the TWRF than population growth, especially under S2 and S3.

4 Conclusions

The findings in this paper show that per capita water requirement for food (CWRF) has increased over three times from 1961 to 2003, largely due to an increase in the consumption of animal products in recent decades. The scenario analysis indicates that future total water requirement for food (TWRF) will likely continue to increase in the next three decades. Even in the low modernization scenario, the shift in food consumption patterns together with population growth may lead to an additional amount of required water of over 400 $km^3 y^{-1}$ in 2030, even after taking technological advances into consideration. This will undoubtedly put high pressure on China's already scarce water resources.

There are three sources of water that can be managed to meet the additional TWRF requirements. The first source is blue water, which is defined as the water in rivers, lakes, reservoirs, ponds and aquifers (Falkenmark, 2003). For food production, blue water means irrigation. However, increasing water scarcity and competition from other sectors have put agricultural blue water use under great pressure. There has been a reallocation of irrigation water to industrial and domestic sectors, and environmental water needs are given more and more weight (Yang and Zehnder, 2001). In China, irrigation water use declined by 15% over 1997–2003 (MWR, 2005). It is difficult to allocate more blue water to future domestic agricultural production.

The second source of water is green water. Green water refers to the water coming from precipitation, stored in the unsaturated soil, and taken up by plants as transpiration (Savenije, 2000). Green water accounts for 73% of the consumptive water use for domestic crop production in China (Liu, 2007), and likely constitutes more than 90% of the water used for the production of animal products. In particular grazing production systems use mostly green water, in which water has almost zero opportunity cost. Although important, green water is often ignored by water managers, largely due to the difficulty to assess or manage it and its low opportunity cost (Liu, 2007). Capturing more green water can be achieved by expanding agricultural land areas, water conservation and by more effectively utilizing local rainfall. Expanding agricultural land areas will not likely be feasible in China. Recent land use trends show a reallocation of agricultural land to other uses (Tan et al., 2005). Effective rainfall management seems a more feasible option to increase the future water supply. Rockström et al. (2003) demonstrated that rainwater harvesting is a promising approach for green water management in the semi-arid tropics of Asia and Africa. Rainfall harvesting has been adopted in the past by many households in the semi-arid areas in China to provide water storage for both irrigation and household usage (Zhao et al., 1995). So far, it has been practiced in 15 provinces, mainly in the North, Northwest, and Southwest China. The potential of additional water supply through rainwater harvesting has never been quantitatively assessed for China.

Obviously a policy towards more rainwater harvesting will affect the partitioning of the rainfall between blue, green and white water. White water is the part of the rainfall that returns to the atmosphere directly by evaporation from intercepted water, and it is not available for blue or green water use (Savenije, 2000). This is the "unproductive" water that can amount to a considerable part of the water balance depending on local conditions (Savenije, 2004), depending primarily on the rainfall distribution over the season and land use. Rainwater harvesting aims at reducing the white (unproductive) use of water and increasing the green water availability by enhancing infiltration from water which would otherwise run off as surface runoff. In doing so, green water management affects the rainwater partitioning of the hydrological cycle in a way that the infiltration increases, the surface runoff (and related erosion) decreases, and as a result the transpiration and percolation increases. For the availability of blue water resources, rainwater harvesting implies a general reduction of blue water, due to a reduction of fast runoff, but it may also lead to an increase of delayed runoff from groundwater seepage. In economic terms the gain in delayed runoff and the related erosion reduction may offset the loss of overall runoff. Clearly the water resources implications of such a green water policy need to be studied in more detail in a river basin context, and particularly the upscaling effect of rainwater harvesting measures, which is also the subject of study in other parts of the world and particularly Africa (e.g. Rockström et al., 2004; Ngigi et al., 2006; Makurira et al., 2007).

The third source of water is virtual water import. Virtual water describes the amount of water consumed in the production process of a product (Allan, 1998). The concept of virtual water import implies that water scarce countries could mitigate water scarcity by importing water intensive food (Chapagain et al., 2006; Hoekstra and Hung, 2005; Yang et al., 2003; Liu et al., 2007b; Liu and Savenije, 2008). Based on the food items looked at in this study, it is estimated that China had a total net virtual water import of 81 $km^3\,y^{-1}$ in 2003, equivalent to 8% of the TWRF. The virtual water strategy has not been consciously used by the Chinese government, largely due to its emphasis on the principle of self-sufficiency in food supply (Liu et al., 2007c). With intensified water scarcity, China's decision makers may have to consider loosening its stance on the self-sufficiency principle and, thereby, taking advantage of virtual water import through the trade of water-intensive foods (Liu and Savenije, 2008).

To conclude, the additional TWRF triggered by the shift of food consumption patterns and population growth will impose high pressure on China's finite water resources. Amongst the other options, two seem feasible to meet the additional water required for food consumption, namely effectively rainfall management and increased virtual water imports. Both options need further study to provide realistic estimates of their potential contribution to mitigating China's water scarcity. Besides, other important ways of decreasing VWC and hence decreasing TWRF could include crop yield improvement through agricultural research and formulation of appropriate agricultural policies. These two options are particularly important given China's continued significant investment in agricultural technology research in the past decades, the food self-sufficiency policy, and the increasing emphasis on reducing the development gap between rural and urban areas, which leads to agricultural policy reform.

A further cause of concern is the high reliance on fertilizers in the high technology development scenario. Particularly the high dependency on phosphate, a mined and finite resource, is worrying. Global phosphate resources are rapidly depleting and without adequate recycling of nutrients (particularly urine) phosphate may become one of the most critical resources for the increasing world population (Steen, 1998; Gumbo, 2005).

Since the requirement of additional water largely depends on food consumption patterns, it is theoretically possible to reduce the additional water requirement by consuming lower amounts of food items with high VWC, such as animal products. Fish could serve as an alternative to meat as a source of protein. Production of sea fish does not require freshwater; hence, replacement of part of meat with sea fish can also save freshwater. Zimmer and Renault (2003) estimated that the VWC of fish is 5 $m^3\,kg^{-1}$ (see Table 1). However, this seems like an over-estimation of the fresh water requirement of fish. Fish from aquaculture requires fresh water in the form of fish feeding and the filling and flushing of fish ponds (which is recycled). Since fish feed mainly relies on the use of manure and offal (a byproduct of animal production), the VWC of fish is not expected to be high. Although detailed computations of virtual water use by fish cultivation are beyond the scope of this paper, it is likely that replacement of meat with fish may imply considerable fresh water savings.

In general, food consumption patterns are closely related to increasing affluence. However, awareness-raising may play a role in affecting the food preference of China's population. Currently, China's meat consumption has exceeded the recommended amounts by the CNS. In addition, some authors have argued that the contemporary Chinese diet shifts may be detrimental to health, by introducing higher incidence of diet-related diseases (Du et al., 2004). Raising public awareness and encouragement of a diet recommended by the CNS may help mitigate the future water scarcity problem in China.

In this paper, we analyze the effect of food consumption patterns on water requirement in an aggregated way for China. It is well known that water scarcity is often a regional problem particularly in the northern part of China, water being more abundant in the southern part of the country. Hence, a more detailed region analysis is useful to compare water requirement with local water resources. However this kind of analysis is limited by data availability. Firstly, regional consumption data for detailed food items are generally lacking. As far as we know, FAO is the best source that provides consumption data for such detailed food items used in this paper. In the Chinese statistical yearbooks, consumption data are generally reported by treating a number of food items as food groups. Examples are consumptions of grain, meat and poultry, eggs, and vegetables. Second, VWC often differs in various locations even for a same food item due to different climatic conditions, soil parameters, and agriculture management, but data on VWC are generally not available at sub-national levels for most food items. Liu et al. (2007a) estimate crop water productivity, or the inverse of VWC, for wheat in China with a spatial resolution of 5 arc-minutes. This estimation is by far the most detailed data for VWC in China. To our best knowledge, the VWC of other food items has not been studied in such a comprehensive way.

The accuracy of the water requirement for food calculated here largely depends on the reliability of the statistical data on food consumption patterns in the FAO's food balance sheets. The food balance sheets are combined every year by FAO by collecting statistical data from its member countries. The quality of the statistics collected differs among countries. For example, it has been reported that the Chinese meat consumption may be understated in the statistics largely due to the inadequately accounting for away-from-home consumption and the underestimation for the migrant workers living in urban areas (Fuller et al., 1999). If this is true, the current water requirement for food consumption is underestimated. An improvement in the quality of the statistical data will no doubt decrease the uncertainty of our calculation.

We acknowledge that the scenario analysis presented in this paper is rather simplified. The society is much more complex than what we have assumed. For example, consumption of animal products may be affected by prices and trade policies, which have not been taken into consideration. Or, future production of animal products such as pork may rely more on maize than in the past. This issue has been disregarded in view of the difficulty to obtain reliable data. Nevertheless, we have made a first attempt to analyze the effect of food consumption pattern on water requirement and we conclude that this influence is substantial under all scenarios.

Although this study focused on China, the impact of the developments studied will have a bearing on water cycles world-wide. As soon as China starts to import "virtual" water, it will certainly impact food prices and production systems in the rest of the world. Moreover, the development sketched in this paper may be exemplary for developments which are likely to occur elsewhere, more particularly on the Indian sub-continent, Africa and South America, where similar dietary changes are taking place. If, in addition, we consider the water demands associated with the expected large scale production of biofuel (e.g. Uhlenbrook, 2007), then considerable changes in the hydrological cycle are likely to occur, worldwide.

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References

Alcamo, J., Henrichs, T., and Rösch, T.: World water in 2025: Global modeling and scenario analysis for the world commission on water for the 21st century, Report A0002, Center for Environmental Systems Research, University of Kassel, Kassel, Germany, 2000.

Allan, J. A.: Virtual water: A strategic resource global solutions to regional deficits, Ground Water, 36, 545–546, 1998.

Chapagain, A. K., and Hoekstra, A. Y.: Water footprints of nations, Value of Water Research Report Series No. 16, UNESCO-IHE, Delft, the Netherlands, 2004.

Chapagain, A. K., Hoekstra, A. Y., and Savenije, H. H. G.: Water saving through international trade of agricultural products, Hydrol. Earth Syst. Sci., 10, 455–468, 2006, http://www.hydrol-earth-syst-sci.net/10/455/2006/.

Christopher, L. D., Courbois, C. B., and Rosegrant, M. W.: Global food demand and the contribution of livestock as we enter the new millennium, International Food Policy Research Institute, Washington, D.C., 1998.

Du, S., Mroz, T. A., Zhai, F., and Popkin, B. M.: Rapid income growth adversely affects diet quality in china–particularly for the poor!, Soc. Sci. Med., 59, 1505–1515, 2004.

Falkenmark, M.: Freshwater as shared between society and ecosystems: From divided approaches to integrated challenges, Philos. Trans. R. Soc. Lond. B. Biol. Sci., 358, 2037–2049, 2003.

FAO: FAO statistical databases: http://faostat.fao.org/default.aspx, last ccess: 10 October 2006, 2006.

Fuller F., Hayes D., and Smith D.: Reconciling Chinese meat production and consumption data, Econ. Dev. Cult. Change, 49(1), 23–43, 2000.

Gerbens-Leenes, P. W. and Nonhebel, S.: Consumption patterns and their effects on land required for food, Ecol. Econ., 42, 185–199, 2002.

Gleick, P. H.: Basic water requirements for human activities: Meeting basic needs, Water Int., 21, 83–92, 1996.

Gumbo, B.: Short-cutting the phosphorus cycle in urban ecosystems. Taylor and Francis Group, London, 320 pp., 2005.

Heilig, G. K.: Chinafood. Can china feed itself? IIASA, Laxenburg, Austria, 1999.

Hoekstra, A. Y. and Chapagain, A. K.: Water footprints of nations: water use by people as a function of their consumption pattern, Water Resour Manag, 21(1), 35–48, 2007.

Hoekstra, A. Y. and Hung, P. Q.: Globalisation of water resources: International virtual water flows in relation to crop trade, Glob. Environ. Change A., 15(1), 45–56, 2005.

Hsu, H. H., Chern, W. S., and Gale, F.: How will rising income affect the structure of food demand? in: China's food and agriculture: Issues for the 21st century, edited by: Gale, F., Economic research service/USDA, Washington, DC, 2002.

Huang, J., Rozell, S., and Rosegrant, M. W.: China's food economy to the twenty-first century; supply, demand, and trade, Econ Devel Cult Change, 47, 737–766, 1999.

Koudstaal, R., Rijsberman, F. R., and Savenije, H. H. G.: Water and sustainable development, Nat. Resour. Forum, 16, 277–290, 1992.

Liu, C. and Yin, R.: Poverty dynamics revealed in production performance and forestry in improving livelihoods: The case of west Anhui, China, For. Policy Econ., 6, 391–401, 2004.

Liu, J.: Modelling global water and food relations; development and application of a GIS-based EPIC model. Dissertation ETH No. 17069, Swiss Federal Institute of Technology, Zürich, 2007.

Liu, J. and Savenije, H. H. G.: Time to break the silence around virtual-water imports. Nature, 453, 587, 2008.

Liu, J., Wiberg, D., Zehnder, A. J. B., and Yang, H.: Modelling the role of irrigation in winter wheat yield, crop water productivity, and production in China. Irrig Sci, 26(1), 21–33, 2007a.

Liu, J., Williams, J. R., Zehnder, A. J. B., and Yang, H.: GEPIC

– modelling wheat yield and crop water productivity with high resolution on a global scale, Agric. Sys., 94, 478–493, 2007b.

Liu, J., Zehnder, A. J. B., and Yang, H.: Historical trends in china's virtual water trade, Water Int, 32, 78–90, 2007c.

Makurira, H., Savenije, H. H. G., Uhlenbrook, S., Rockström, J., and Senzanje, A.: Towards a better understanding of water partitioning processes for improved smallholder rainfed agricultural systems: A case study of Makanya catchment, Tanzania. Phys. Chem. Earth, 32, 1082–1089, 2007.

MWR: China water resources bulletins, Ministry of Water Resources, Beijing, http://www.mwr.gov.cn/, 2005.

Ngigi, S. N., Rockström, J., and Savenije, H. H. G.: Assessment of rainwater retention in agricultural land and crop yield increase due to conservation tillage in Ewaso Ng'iro river basin, Kenya, Phys. Chem. Earth, 31, 910–918, 2006.

Oki, T. and Kanae, S.: Global hydrological cycles and world water resources, Science, 313, 1068–1072, 2006.

Postel, S. L., Daily, G. C., and Ehrlich, P. R.: Human appropriation of renewable fresh water, Science, 271, 785–788, 1996.

Raskin, P., Gleick, P., Kirshen, P., Pontius, G., and Strzepek, K.: Water futures: Assessment of long-range patterns and prospects, Stockholm Environment Institute, Stockholm, Sweden, 1997.

Renault, D. and Wallender, W. W.: Nutritional water productivity and diets, Agric Water Manag, 45, 275–296, 2000.

Rijsberman, F. R.: Water scarcity: Fact or fiction? Agric Water Manag, 80, 5–22, 2006.

Rockström, J.: Water for food and nature in drought-prone tropics: Vapour shift in rain-fed agriculture, Philos. Trans. R. Soc. Lond. B. Biol. Sci., 358, 1997–2009, 2003.

Rockström, J., Folke, C., Gordon, L., Hatibu, N., Jewitt, G., de Vries, F.P., Rwehumbiza, F., Sally, H., Savenije, H., and Schulze, R.: A watershed approach to upgrade rainfed agriculture in water scarce regions through Water System Innovations: an integrated research initiative on water for food and rural livelihoods in balance with ecosystem functions, Phys. Chem. Earth, 29(15–18), 1109–1118, 2004.

Savenije, H. H. G.: Water scarcity indicators; the deception of the numbers, Phys Chem Earth, 25, 199–204, 2000.

Savenije, H. H.G.: The importance of interception and why we should delete the term evapotranspiration from our vocabulary. Hydrological Processes, 18(8), 1507–1511, 2004.

Seckler, D., Amarasinghe, U., Molden, D. J., de Silva, R., and Barker, R.: World water demand and supply, 1990 to 2025: Scenarios and issues, IWMI research report 19, IWMI Research Report 19, IWMI, Colombo, Sri Lanka, 1998.

Shiklomanov, I. A.: The world's water resources, in: Proceedings of the international symposium to commemorate 25 years of the ihp, UNESCO/IHP, Paris, France, 93–126, 1991.

Steen. P.: Phosphorus availability in the 21st Century: management of a nonrenewable resource, Phosphorus and Potassium Journal, 217, 1998. (available from: http://www.nhm.ac.uk/research-curation/projects/phosphate-recovery/p&k217/steen.htm)

Tan, M., Li, X., Xie, H., and Lu, C.: Urban land expansion and arable land loss in china–a case study of beijing-tianjin-hebei region, Land Use Policy, 22, 187–196, 2005.

United Nation: World population prospects: The 2006 revision, United Nations, New York, 2006.

Uhlenbrook S.: Biofuel and water cycle dynamics: what are the related challenges for hydrological processes research? Hydrol Process, 21 (26): 3647–3650, 2007.

Vörösmarty, C. J., Green, P., Salisbury, J., and Lammers, R. B.: Global water resources: Vulnerability from climate change and population growth, Science, 289, 284–288, 2000.

World Bank: China 2020 – at china's table. Food security options, World Bank, Washington, D.C., 1997.

Xu, F. A. and Zhao, B. Z.: Development of crop yield and water use efficiency in fengqiu county, china, Acta Pedologica Sinica, 38, 491–497, 2001.

Yang, H. and Zehnder, A. J. B.: China's regional water scarcity and implications for grain supply and trade, Environ. Plann. A., 33, 79–95, 2001.

Yang, H., Reichert, P., Abbaspour, K. C., and Zehnder, A. J. B.: A water resources threshold and its implications for food security, Environ. Sci. Technol., 37, 3048–3054, 2003.

Zhang, D.: Virtual water trade in China with a case study for the Heihe river basin, MSc thesis, UNESCO-IHE, Delft, the Netherlands.

Zhao, S. L., Li, F. R., and Wang, J.: On the development of water harvesting agriculture in the semiarid area northwest china, Acta Bot. Boreal. Occident. Sin, 15, 9–13, 1995.

Zimmer, D. and Renault, D.: Virtual water in food production and global trade: Review of methodological issues and preliminary results, in: Virtual water trade. Proceedings of the international expert meeting on virtual water trade, edited by: Hoekstra, A. Y., UNESCO-IHE, Delft, the Netherlands, 25–47, 2003.

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A GIS-based tool for modelling large-scale crop-water relations

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Recent research on crop-water relations has increasingly been directed towards the application of locally acquired knowledge to answering the questions raised on larger scales. However, the application of the local results to larger scales is often questionable. This paper presents a GIS-based tool, or a GEPIC model, to estimate crop water productivity (CWP) on the land surface with spatial resolution of 30 arc-min. The GEPIC model can estimate CWP on a large-scale by considering the local variations in climate, soil and management conditions. The results show a non-linear relationship between virtual water content (or the inverse of CWP) and crop yield. The simulated CWP values are generally more sensitive to three parameters, i.e. potential harvest index for a crop under ideal growing conditions (HI), biomass-energy ratio indicating the energy conversion to biomass (WA), and potential heat unit accumulation from emergence to maturity (PHU), than other parameters. The GEPIC model is a useful tool to study crop-water relations on large scales with high spatial resolution; hence, it can be used to support large-scale decision making in water management and crop production.

Software availability

Name of software: GEPIC
Program language: Visual Basic for Applications (VBA), ArcObject
Developer: Swiss Federal Institute of Aquatic Science and Technology (Eawag)
Contact address: Swiss Federal Institute of Aquatic Science and Technology (Eawag), Ueberlandstrasse 133, CH-8600, Duebendorf, Switzerland
Software required: ArcGIS 9.1
Availability: can be made available to researchers on request to the author.

1. Introduction

Water is indispensable for crop production. Dependence on water comes from the intrinsic process of crop growth. This process requires carbon dioxide (CO_2), and exposes a plant's interior to the drying power of the atmosphere (Holbrook and Zwieniecki, 2003). When plants absorb less water through their roots than is transpired from their leaves, water stress develops. As a result, stomatal pores in the leaf surface progressively close (Lauer and Boyer, 1992; Lawlor, 1995). This stomatal closure not only decreases the rate of transpiration (Gimenez et al., 1992; Lauer and Boyer, 1992; Ort et al., 1994), but also reduces photosynthetic assimilation of CO_2, posing constraints on plant growth (Lauer and Boyer, 1992; Quick et al., 1992; Ort et al., 1994). Water stress substantially alters plant's metabolism, decreases plant growth and photosynthesis and profoundly affects ecosystems and agriculture, and thus human societies (Lawlor, 1995; Evans, 1998; Tezara et al., 1999).

Defined as the ratio of crop yield to crop evapotranspiration, crop water productivity (CWP) combines two important and interrelated processes in agricultural systems, and it is an important indicator for measuring the quantitative relations between crop production and water consumption (Liu et al., 2007a,b). Another concept, virtual water content (VWC), has recently been introduced to express the amount of water consumed in terms of evapotranspiration to produce a unit of crop product (Hoekstra and Hung, 2005). VWC is the inverse of CWP. Recent efforts in CWP and VWC studies are increasingly being directed towards the application of knowledge acquired on small spatial scales to answering questions raised on larger scales. Zwart and Bastiaanssen (2004) review local measurements of CWP from 84 literature sources and discuss general patterns of CWP in relation to climate, irrigation and soil nutrient management on a global scale. Hoekstra and Hung (2005) calculate the values of VWC based on the climate station data in the capital city of individual countries, and then quantify the volumes of virtual water flows among nations through international crop trade. Rockström et al. (2007) develop a CWP function based on a number of empirical field observations of grains in both tropical and temperate environments, and assess the water challenge of attaining the 2015 hunger targets in 92 developing

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countries set out in the United Nations Millennium Development Goals. It needs to be pointed out that the locally valid findings may not be representative of other locations, and the application of the local results to larger scales is questionable. There is an increasing need for a new research tool that is capable of studying large-scale crop-water relations, and that considers, in the mean time, local variations.

Previously, several models have been developed to study food production on large scales. Some of the models regard water as an influencing factor in crop production. In this paper, the large-scale food production models are first reviewed. Their advantages and disadvantages in studying crop-water relations are emphasized. Then, a GEPIC model is introduced as an effective tool for conducting a global crop-water relation study. The model is applied to estimate the CWP of three major cereal crops (wheat, maize and rice) on a global scale, and the results are compared with other studies.

2. Large-scale food production models

In the literature, models applied in food production studies on global and national scales mainly fall into six major categories: physical models, economic models, physical-economic models, time series models, regression analysis models, and integrated models. An overview of these models is presented below, and the summary is given in Table 1. Two issues are emphasized here, namely the ability to study crop-water relations, and spatial resolution.

Crop growth models are a type of commonly used physical model. Crop growth models often simulate crop growth with some empirical functions or model the underlying physiological processes of crop growth in relation to the surrounding environment. A number of crop growth models have been developed and widely used, such as EPIC (Williams et al., 1989), DSSAT (IBSNAT, 1989), WOFOST (Hijmans et al., 1994), CropSyst (Stockle et al., 1994), YIELD (Burt et al., 1981), CropWat (Clarke et al., 1998) and CENTRURY (Parton et al., 1992). Most existing crop growth models are mainly used for point or site specific applications (Priya and Shibasaki, 2001; Liu et al., 2007b). Crop growth models are rarely used alone for food production studies on a global or national scale. However, combining crop growth models with other techniques is a common way to extend the applicability of these models for large-scale studies, which will be introduced later. The Agro-ecological Zones (AEZ) approach is another example of the physical model. The AEZ approach uses a land resources inventory to assess all feasible agricultural land-use options for specific management conditions and levels of inputs, and to quantify the expected production of relevant cropping activities (Fischer et al., 2002). The AEZ approach can provide answers to what-if scenarios such as establishing what the global food production is if there are high levels of water inputs. A major drawback is that the levels of irrigation inputs can be set only as low, medium and high. It is impossible to make good quantifications; hence, the quantitative analysis of crop-water relations is difficult to achieve.

The World Food Model developed by the Food and Agriculture Organization of the United States (FAO) is a typical economic model to simulate and project global food production. This model is a price-equilibrium, multi-commodity model, and it is designed to provide year-by-year world price-equilibrium solutions for 40 agricultural products (Frohberg and Britz, 1994). In this model, the main components are the supply and demand equations, and the market clearing mechanism. Only the economic factor, or price, is considered for global food production; all other equally important factors, including water, are ignored.

The IMPACT model (International Model for Policy Analysis of Agricultural Commodities and Trade) is a typical example of the physical-economic model. This model examines the effects of various food policies, the impact of different rates of agricultural research investment on crop productivity, and the impact of income and population growth on long-term food demand and supply balances and food security (Rosegrant et al., 2001). The model comprises a set of 36 country or regional sub-models, each determining supply, demand, and prices for 32 agricultural commodities. The country and regional agricultural sub-models are linked through trade. In light of the importance of water for food production, the IMPACT-WATER model was developed to integrate the IMPACT model with a Water Simulation Model (Rosegrant et al., 2002). The IMPACT-WATER model uses a finer disaggregation of 69 river basins in recognition of the fact that significant climate and hydrologic variations within regions make the use of large spatial

Table 1
Overview of the conventional model approaches for the study of food production on global or national scales

Model type	Typical examples	Inputs	Spatial resolution	Scale	Major shortcomings
1.Physical model	1.1 Crop growth models[a]	Climate, soil, land, irrigation, fertilizer etc.	Local	Site	Point or site-specific application
	1.2 Agro-ecological zones (AEZ)	Climate, soil, land, irrigation, fertilizer etc.	30 arc-minutes	Global	No quantification of irrigation and fertilizer; seperate consideration of soil and climate
2. Economic model	2.1 FAO World Food Model	Price	National	Global	Only price is considered the influencing factor
3. Physical-economic model	3.1 IMPACT	Food policy, research investment, income, price	Regional or national	Global	Low spatial resolution; no consideration of water, fertilizer, soil nutrient and land-use
	3.2 IMPACTWATER	Food policy, research investment, income, price, water	Regional or national	Global	Low spatial resolution; no consideration of fertilizer, soil nutrient and land-use
4. Time series model	4.1 Linear yield growth model	Yield growth rate, time	Regional or national	Global or national	Poor accuracy; lack of ability to analyze the impacts of irrigation and fertilizer on crop production
5. Regression analysis model	5.1 Yield as a function of influencing factors	Precipitation, irrigation, fertilizer, GDP, latitude (one or many of them)	Regional or national	Global or national	Poor accuracy, low spatial resolution
6. Integrated model	6.1 Crop growth model + regression	Climate, soil, land, management	Regional or national	Global or national	Whether yield function derived from reference sites can be extrapolated to other locations is uncertain
	6.2 Crop growth model + GIS	Climate, soil, land, management	30 arc-min or even higher	Global or national	Development and application have a recent origin

[a] Crop growth models alone are rarely used for studies on global or national scales. They are presented in the table because they are often applied in the integrated models.

units inappropriate for water resource assessment and modelling. For both the IMPACT and IMPACT-WATER models, the assessments conducted on the national or regional scale disguise spatial variations within a country or region.

The time series methods assume that yield is a function of time and yield growth rate (Doos and Shaw, 1999; Dyson, 1996; Tweeten, 1998). Linear yield growth models are constructed to estimate the yield growth rates with past yield trends. Then the yield growth rates experienced in history were used to project the regional or national yield in the future (Dyson, 1999). The PODIUM model developed by the International Water Management Institute (IWMI) takes this approach. PODIUM projects national food production based on expected yields and cultivated area under both irrigated and rainfed conditions (Seckler et al., 1998). The yield and cultivated area in the future are based on past trend, or user-defined scenarios. The time series models consider no other influencing factors such as irrigation or fertilizer application rates; hence, they are unable to analyze the impacts of these factors on crop production. In addition, low accuracy limits the application of the time series methods (Tan and Shibasaki, 2003).

For regression analysis models, regression equations are developed from observed data to link crop yield to several influencing factors such as precipitation, temperature, irrigation or fertilizer (Rosenzweig et al., 1999). The crop-water relation can be analyzed when the regression analysis is conducted between crop yield and water-related variables such as precipitation and irrigation. Here accuracy is the limiting factor (Tan and Shibasaki, 2003).

There are studies integrating crop growth models with regression analysis. Statistical analyses are used to derive agro-climatic regional yield transfer functions from previously simulated site-level results (Rosenzweig and Iglesias, 1998; Parry et al., 1999; Rosenzweig et al., 1999; Iglesias et al., 2000). The yield transfer functions can include the influencing factors of precipitation and irrigation. These functions are then applied to the spatial input data to estimate crop yield in different locations. It remains to be seen whether the transfer function derived from one geographic location can be extrapolated to other locations.

Integrating crop growth models with a Geographic Information System (GIS) is another type of integrated model. Combined with the powerful function of spatial data storage and management in a GIS, a crop growth model may be extended to address spatial variability of yield as affected by climate, soil, and management factors. There have been some preliminary attempts to integrate crop growth models with a GIS (Curry et al., 1990; Rao et al., 2000; Priya and Shibasaki, 2001; Ines et al., 2002; Stockle et al., 2003), and these attempts mainly focus on scales no higher than national ones. Recent research has integrated the EPIC model with a GIS for global-scale studies (Tan and Shibasaki, 2003; Liu et al., 2007a,b). In this paper, the GEPIC model developed in the Swiss Federal Institute of Aquatic Science and Technology is introduced, and it is applied to simulate CWP of wheat, maize and rice.

3. Description of the GEPIC model

3.1. Framework of the GEPIC model

GEPIC is a GIS-based crop growth model integrating a bio-physical EPIC model (Environmental Policy Integrated Climate) with a GIS to simulate the spatial and temporal dynamics of the major processes of the soil–crop–atmosphere-management system (Liu et al., 2007a,b). The general idea of the GEPIC model is expressed in Fig. 1. The EPIC model is designed to simulate crop-related processes for specific sites with site-specific inputs. By integrating EPIC with a GIS, the GEPIC model treats each grid cell as a site. It simulates the crop-related processes for each predefined grid cell with spatially distributed inputs. The inputs are provided to the model in terms of GIS raster maps as well as text files. Necessary maps include land-use maps, elevation and slope maps, irrigation maps, fertilizer maps, climate code maps, and soil code maps. The land-use maps provide information on crop distribution (code 0 indicates absence of a specific crop, while 1 and 2 indicate existence of the crop under rainfed and irrigated conditions, respectively). The elevation and slope maps show the average elevation and slope in each grid cell. The irrigation and fertilizer maps show the annual maximum irrigation depth and fertilizer application rate. The climate and soil code maps indicate the code numbers of the climate and soil files in each grid cell. These code numbers correspond to the text files of climate and soil data. Climate files contain daily weather data (e.g. daily precipitation, daily minimum and maximum temperatures) and monthly weather statistics. Soil files contain several soil parameters (e.g. soil depth, percent sand and silt, pH, organic carbon content, etc). Annual irrigation and fertilizer inputs are provided in the irrigation and fertilizer maps. The outputs of the GEPIC model are raster GIS maps representing the spatial distribution of output variables such as crop yield and evapotranspiration.

To develop such a GIS-based crop growth model, the ESRI's GIS software ArcGIS 9.1 was selected mainly due to its wide application. The well-documented ArcObjects libraries were also an important reason for the selection. The ArcObjects libraries allow any available function of ArcGIS to be exploited. In addition, the functionality can be further extended by using third-party Component Object Model-compliant (COM-compliant) programming languages such as Visual Basic, C++, Java, or Python (ESRI, 2004). Visual Basic for Applications (VBA) in ArcGIS were used to develop the GEPIC model mainly due to two reasons. First, VBA is a built-in language within ArcGIS. The use of VBA requires no external development environment. Second, nowadays online forum has become an effective way for program developers to seek similar solutions to complex programming problems. While the solutions are similar in many COM-compliant languages, most solutions are provided in online forums in the Visual Basic context (Stevens et al., 2007).

In the GEPIC model, ArcGIS is used as an application framework, input editor, and map displayer. As an application framework, ArcGIS provides the main programming language VBA to design the interface of GEPIC, and to design programs for input data access, text output data generation, and output map creation. As an input editor, ArcGIS is used to convert vector input data into raster data, which are the main input format. One typical example is the climate data. Daily climate data are often available for various stations, while the code of each station is presented as attributed point data. The point data is converted into raster data with a method of Thiessen Polygons, with which the daily climate data from the closest climate station is used as a representative for a grid cell (Liu et al., 2007b). As a map displayer, ArcGIS can be used to visualize the GIS data (e.g. vector or raster input data; raster output data etc).

The GEPIC software comprises three components. The most obvious component is the proprietary GIS, which is a standard ArcMap window in ArcGIS 9.1. The least obvious component is the EPIC model, which is the core of all simulations. The third component is the GEPIC interface (see Fig. 2), and it links GIS and EPIC. The interface contains toolbars and menus. The toolbars provide functional buttons to locate raster input data sets, to select the simulated area and crops, and to specify spatial resolution, and to set the locations of the EPIC file, and input and output files. It further provides buttons to edit inputs into EPIC required input files, to run the EPIC model, and to generate output maps. The menu has submenus, which allow users to perform the same tasks as the toolbars.

3.2. The crop growth model

Crop growth is simulated with a daily time step by modelling leaf area development, light interception, and conversion of intercepted light into biomass. The daily potential increase in biomass is estimated with Monteith's approach (Monteith, 1977):

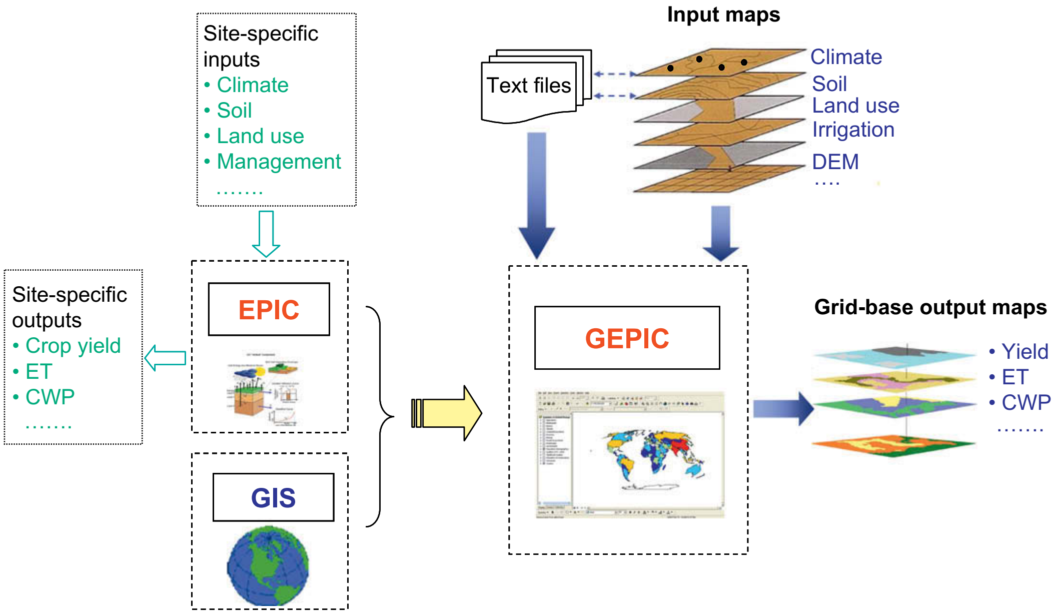

Fig. 1. General framework of the GEPIC model.

$$\Delta B_{p,i} = 0.001 \times \mathrm{WA} \times \mathrm{PAR}_i \quad (1)$$

where ΔB_p is daily potential increase in biomass in kg ha^{-1} in day i, WA is a biomass-energy ratio indicating the energy conversion to biomass in (kg ha^{-1})(MJ m^{-2})$^{-1}$, PAR is intercepted photosynthetic active radiation in MJ m^{-2} d^{-1}, and it is estimated with Beer's law equation (Monsi and Saeki, 1953) as follows:

$$\mathrm{PAR}_i = 0.5\mathrm{RA}_i\left(1 - \mathrm{e}^{-0.65\mathrm{LAI}_i}\right) \quad (2)$$

Where RA is solar radiation in MJ m^{-2}, LAI is the leaf area index, and the constant 0.5 is used to convert solar radiation to photosynthetically active radiation.

The potential biomass is adjusted daily if any of the five stress factors (water stress, temperature stress, nitrogen stress, phosphorus stress and aeration stress) is less than 1.0 using the equation

$$\Delta B_{a,i} = \Delta B_{p,i}\gamma_{\mathrm{reg},i} \quad (3)$$

where ΔB_a is the daily actual increase in biomass in kg ha^{-1}, and γ_reg is the crop growth regulation factor, which is the minimum of the

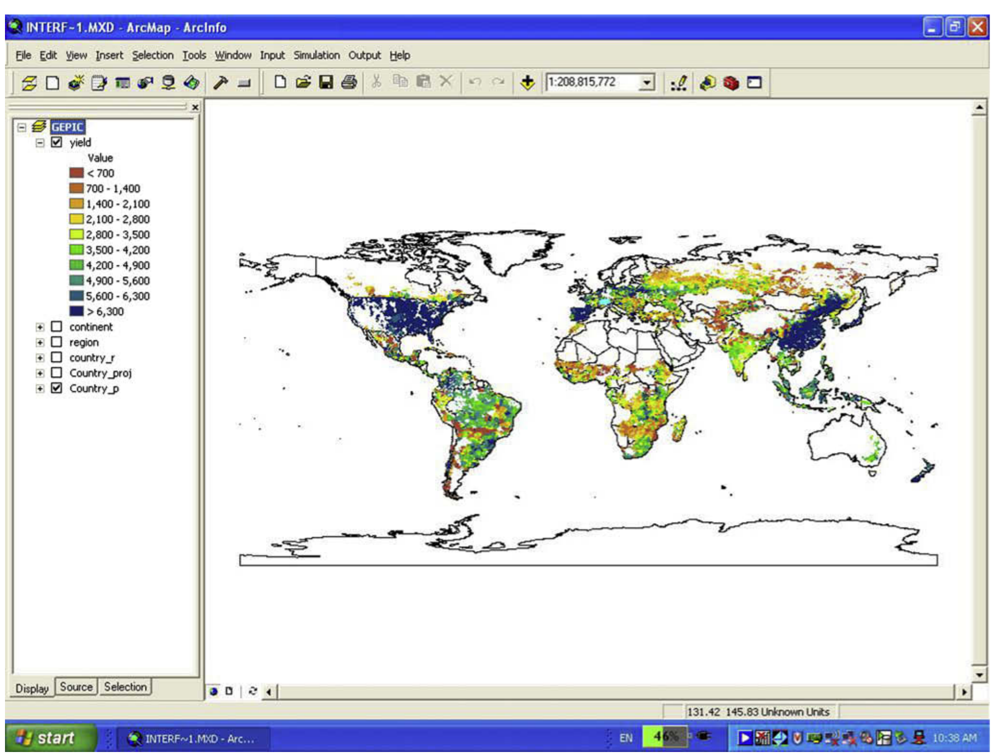

Fig. 2. Interface of the GEPIC software.

above five stress factors. Details for estimate γ_{reg} can be found in Williams et al. (1989).

Above-ground biomass on the day of harvest is calculated as the sum of the daily actual increase in biomass in growing season:

$$B_{AG} = \sum_{i=1}^{N} \Delta B_{a,i} \tag{4}$$

where B_{AG} is the above-ground biomass on the day of harvest in kg ha^{-1}, N is the number of days from planting date to harvest date.

Crop yield is estimated using the harvest index concept:

$$\text{YLD} = \text{HIA} \times B_{AG} \tag{5}$$

where YLD is the amount of economic dry yield that could be removed from the field in kg ha^{-1}, and HIA is the water stress adjusted harvest index. For non-stressed conditions, the harvest index increases non-linearly from zero at planting to the potential harvest index at maturity. The harvest index is reduced by water stress using the following equation (Williams et al., 1989):

$$\text{HIA}_i = \text{HIA}_{i-1} - \text{HI}\left(1 - \frac{1}{1 + \text{WSYF} \times \text{FHU}_i(0.9 - \text{WS}_i)}\right) \tag{6}$$

where HI is the potential harvest index on the day of harvest, WSYF is a crop parameter expressing the sensitivity of harvest index to drought, FHU is a crop growth stage factor, and WS is the water stress factor, and subscript i and $i-1$ are the Julian days of the year.

3.3. Soil evaporation and crop transpiration

Reference evapotranspiration is simulated as a function of extraterrestrial radiation and air temperature with Hargreaves method (Hargreaves and Samani, 1985):

$$\lambda \text{ET}_0 = 0.023 H_0 (T_{mx} - T_{mn})^{0.5} (T_{av} + 17.8) \tag{7}$$

whereλ is the latent heat of vaporization in MJ kg^{-1}, ET_0 is the reference evapotranspiration in mm d^{-1}, H_0 is the extraterrestrial radiation in MJ m^{-2} d^{-1}, T_{mx}, T_{mn}, and T_{av} are the maximum, minimum and mean air temperature for a given day in °C.

Evaporation from soil and transpiration from plants are calculated separately by an approach similar to that of Ritchie (1972). Potential transpiration is simulated as a linear function of ET_0 and leaf area index (LAI).

$$T_p = \text{ET}_0 \text{LAI}/3 \quad 0 < \text{LAI} < 3 \tag{8}$$

$$T_p = \text{ET}_0 \quad \text{LAI} \geq 3 \tag{9}$$

where T_p is the potential transpiration in mm d^{-1}, and LAI is the leaf area index.

Potential evaporation is simulated with Eq. (10):

$$E_p = \max\{(\text{ET}_0 - I)\lambda_s, \ 0\} \tag{10}$$

where E_p is the potential soil evaporation in mm d^{-1}, I is the rainfall interception in mm d^{-1}, and λ_s is a soil cover index.

When $\text{ET}_0 < I$, the actual plant transpiration (T_a) and soil evaporation (E_a) are set to zero. Otherwise, they are calculated as follows:

$$T_a = \min\{\text{ET}_0 - I, T_p\} \tag{11}$$

$$E_a = \min\{E_p, E_p(\text{ET}_0 - I)/(E_p + T_a)\} \tag{12}$$

The actual evapotranspiration (ET_a) is the sum of actual soil evaporation and crop transpiration.

3.4. Sensitivity analysis

There are several methods to perform sensitivity analysis. These methods range from the quantitative sampling-based methods to other forms of global sensitivity with regional properties, down to the simplest class of the One Factor At a Time (OAT) screening techniques (Campolongo et al., 2007). The most commonly used method is sampling-based. Sampling-based sensitivity analysis is one in which the model is executed repeatedly for a large number of parameter combinations, in which parameter values are sampled from a certain distribution of the parameters. Although commonly used, the method is not practical here due to high computing costs. For sampling-based sensitivity analysis, the number of parameter combinations should be relatively large (approximately 500–1000). In this study, over 15,000 simulations are performed for each crop (i.e. 25,783 for wheat, 26,896 for maize, and 15,796 for rice) on a global scale for one set of parameter combinations. To reduce computation load, algebraic sensitivity analysis is proposed to find algebraically the sensitivities of output to variations in contributing factors (Norton, 2008). However, the results of the algebraic sensitivity analysis often become too complicated to derive and interpret as more equations are analyzed (Norton, 2008). This shortcoming limits the application of the algebraic sensitivity analysis to the GEPIC model, which consists of several interrelated complex components, such as crop growth component, hydrological component and nutrient cycle component. Each of the components includes several equations (the main equations used for the calculation of crop growth and crop evapotranspiration are described in Section 3.2 and 3.3). For practical reasons, the simplest method, or the OAT method, is applied to examine the relative sensitivity of CWP to several important parameters. In the OAT method only one factor, X_i, varies at a time while other factors are fixed. The change in model output can then be unambiguously attributed to such a change in factor X_i. A relative sensitivity index, defined as the ratio between the relative normalized change in output to the normalized change in related input, was calculated to indicate the magnitude of the sensitivity of the model output to the input factors (Brunner et al., 2004). The relative sensitivity index S in Eq. (13) developed by McCuen (1973) was slightly modified (Eq. (14)) to consider the absolute change in model output and related input (Wang et al., 2005b):

$$S = \frac{\Delta Y}{\Delta X}\frac{X}{Y} \tag{13}$$

$$S_i = \frac{|Y(X_1, \ldots, X_i + \Delta X_i, \ldots X_p) - Y(X_1, \ldots, X_i, \ldots X_p)|}{Y(X_1, \ldots, X_i + \Delta X_i, \ldots X_p)} \frac{X_i}{|\Delta X_i|} \tag{14}$$

where S_i is a sensitivity index indicating the relative partial effect of parameter X_i on model output Y, p is the total number of parameters considered, and Y is the model output (i.e. CWP in this study), $\triangle X$ is a small change in X, $\triangle Y$ is the change in Y in response to the change in X.

The selection of important parameters that are closely related to CWP is mainly based on literature review and expert judgment. The simulation of CWP depends on the simulation of two processes: crop yield and crop evapotranspiration. Wang et al. (2005a) reported that the following six parameters are the most important for the related processes: biomass-energy ratio (WA), potential harvest index (HI), potential heat unit (PHU), water stress-harvest index (PARM3), SCS curve number index coefficient (PARM42), and the difference in soil water contents at field capacity and wilting point (DIFFW). DIFFW is not used for sensitivity analysis in this paper because it is not a parameter directly used in the EPIC model. In this study, the sensitivity of CWP to all the other five parameters is analyzed. For each grid cell, CWP is first calculated with default parameter values; then, CWP is simulated by increasing and decreasing the default parameter values by 10%. Based on Eq. (14), two values of the sensitivity index are calculated for each of the five parameters in each grid cell. We present the average of these two values as follows:

$$\overline{S}_i = \frac{1}{2}\left(\frac{|\mathrm{CWP}_{1.1X_i} - \mathrm{CWP}_{X_i}|}{0.1\mathrm{CWP}_{X_i}} + \frac{|\mathrm{CWP}_{0.9X_i} - \mathrm{CWP}_{X_i}|}{0.1\mathrm{CWP}_{X_i}}\right) = \frac{|\mathrm{CWP}_{1.1X_i} - \mathrm{CWP}_{X_i}| + |\mathrm{CWP}_{0.9X_i} - \mathrm{CWP}_{X_i}|}{0.2\mathrm{CWP}_{X_i}} \quad (15)$$

where $\overline{S}_i$ is the sensitivity index of parameter X_i, CWP_{xi} is the crop water productivity simulated by setting all parameters to default values, $CWP_{1.1xi}$ is the crop water productivity simulated by setting all parameters to default values except X_i, which is set to 110% of its default value, and $\mathrm{CWP}_{0.9xi}$ is the crop water productivity simulated by setting all parameters to default values except $\mathrm{X_i}$, which is set to 90% of its default value.

Five $\overline{S}_i$ values are first calculated in each grid cell corresponding to the five selected parameters. The parameter with the highest $\overline{S}_i$ is defined as the most sensitive parameter.

4. An illustration of the application of the GEPIC model

4.1. Case study and data sources

This study demonstrates the simulated CWP of wheat, maize, and rice at the global level in the year of 2000. These three crops accounted for about 76% of the global cereal harvested area and 86% of global cereal production in 2004 (FAO, 2006). The simulation is based on the crop distribution maps of these crops from Leff et al. (2004). The distribution maps have a spatial resolution of 30 arc-min (about 50 km × 50 km in each grid near the equator), and describe the fraction of a grid cell occupied by each of the crops. To determine whether crops are planted under rainfed or irrigated conditions, the irrigation map from Döll and Siebert (2000) was employed in combination with the crop distribution maps. When irrigation is equipped, all crops are assumed to be planted under irrigated conditions. Otherwise, they are categorized as being planted under rainfed conditions. Daily precipitation and daily maximum and minimum temperatures were collected for 11,729 meteorological stations from two sources: the Global Daily Climatology Network and the National Climate Data Center. Spatial distributed soil parameters were mainly derived from the Digital Soil Map of the World (FAO, 1990) and the International Soil Profile Data Set (Batjes, 1995). The amount of fertilizer applied per country and crop was derived from the international fertilizer industry association (IFA/IFDC/IPI/PPI/FAO, 2002).

4.2. Validation

There are several difficulties in validating the simulated results in this study. First, there are no high-resolution maps indicating spatial distribution of measured or statistical crop yield or CWP on a global scale. This makes grid-to-grid comparison between the simulated and statistical yields impossible. Second, although national statistics on crop yields are available from FAO (2006), few countries have reported national statistics on crop evapotranspiration or CWP. Considering the scarcely available data, the GEPIC model was validated in two ways. First, simulated national average yields, which were calculated based on the simulated crop yields and crop areas in each grid cell, were compared with the statistical national average yields from FAO (2006). Second, measured CWP values are often reported in literature for several agricultural experiment stations. These reported values were compared with the simulated CWP values in the grid cells where the stations are located.

It is worth noting that the crop distribution maps used in this paper are not completely consistent with FAO statistics. For instance, according to the crop distribution maps, rice is not planted in Algeria, but FAO has reported crop yield of rice there (although the total harvest area is lower than 200 ha in 2000 for the entire country). Here, only the countries where crop areas are reported in both the sources were compared, i.e. 102 countries for wheat, 124 countries for maize, and 103 countries for rice.

The comparison is shown in Fig. 3. The simulated yields and the statistical yields are quite comparable, as indicated by highly significant *F*-tests (the *P* values are all higher than 99%). For all the three crops, the trend lines are close to the 1:1 lines, and the R^2 values are higher than 0.6. Particularly for wheat, the R^2 value is almost 0.95. All the slopes of the trend lines are not significantly different from 1, while all the intercepts are not significantly different from 0. Considering the fact that this study uses default parameters in the EPIC model without conducting a model calibration (mainly due to the lack of measured or statistical data), the simulated results are regarded as very satisfactory for the three crops.

The simulated CWP at several sites was compared with the measured CWP as shown in Table 2. All the measured CWP values were obtained from a reviewer paper by Zwart and Bastiaanssen

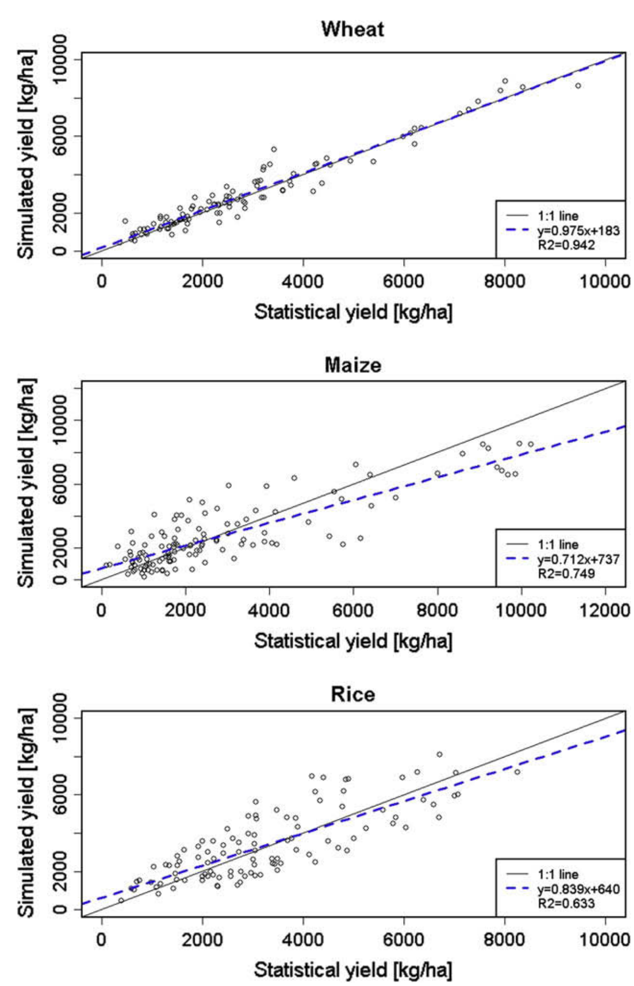

Fig. 3. Comparison between simulated yields and FAO statistical wheat yields in 2000.

Table 2
Comparison of the simulated CWP values with the measured CWP values

Location name	Measured CWP			Simulated CWP	Whether simulted CWP is within the range of the measured CWP
	Min kg/m^3	Max kg/m^3	Mean kg/m^3	kg/m^3	
Wheat					
Parana, Argentina	0.55	1.49	1.04	0.65	Yes
Merredin, Australia	0.56	1.14	0.95	0.82	Yes
Benerpota, Bangladesh	0.52	1.34	0.91	0.99	Yes
Quzhou, China	1.38	1.95	1.58	0.84	Yes
Xifeng, China	0.65	1.21	0.84	0.41	No
Luancheng, China	1.07	1.29	1.26	1.23	Yes
Yucheng, China	0.88	1.16	1.04	1.01	Yes
Beijing, China	0.92	1.55	1.19	1.23	Yes
West Bengal, India	1.11	1.29	1.19	0.87	No
Pantnagar, India	0.86	1.31	1.11	0.83	No
Karnal, India	0.27	0.82	0.67	0.49	Yes
Meknes, Morocco	0.11	1.15	0.58	0.48	Yes
Sidi El Aydi, Morocco	0.32	1.06	0.61	0.45	Yes
Faisalabad,Pakistan	0.7	2.19	1.28	0.70	Yes
Tel Hadya, Syria	0.48	1.1	0.78	0.56	Yes
Yellow Jacket (CO), USA	0.47	1.08	0.77	0.56	Yes
Grand Valley(CO), USA	1.53	2.42	1.72	0.96	No
Tashkent, Uzbekistan	0.44	1.02	0.73	0.75	Yes
Maize					
Azul, Argentina	1.84	2.79	2.35	1.33	No
Guaira, Brazil	1.13	1.33	1.21	1.73	No
Xifeng, China	1.26	2.31	2.00	1.94	Yes
Changwu, China	1.36	1.65	1.56	1.85	No
Yucheng, China	1.63	2.22	*1.93*	1.76	Yes
Luancheng, China	1.55	1.84	*1.70*	1.82	Yes
Pantnagar, India	1.17	1.74	1.47	1.44	Yes
Tal Amara, Lebanon	1.36	1.89	1.64	1.52	Yes
Sevilla, Spain	1.5	2.16	1.73	1.60	Yes
Szarvas, Hungary	1.28	2.44	1.85	1.30	Yes
Harran plain, Turkey	1.94	2.25	2.02	1.51	No
Cukurova, Turkey	0.22	1.25	1.01	1.73	No
Bushland, USA	0.89	1.74	*1.32*	1.49	Yes
Garden City, USA	0.83	1.68	1.26	1.51	Yes
Blacksburg, USA	1.34	3.26	2.67	1.82	Yes
Oakes, USA	2.03	2.86	2.55	2.16	Yes
Rice					
Zhanghe, China	1.04	2.2	1.41	1.18	Yes
Nanchang, China	1.63	2.04	1.84	1.88	Yes
Pantnagar, India	0.8	0.99	0.89	0.93	Yes
Raipur, India	0.46	0.82	0.46	0.46	Yes
New Delhi, India	0.55	0.67	0.67	0.33	No
Punjab, India	0.87	1.46	1.15	1.08	Yes
Muda, Malaysia	0.48	0.62	0.54	1.27	No
Kadawa, Nigeria	0.5	0.79	0.59	0.60	Yes
Luzon, Philippines	1.39	1.61	*1.50*	1.21	No
Beaumont, USA	1.37	1.44	*1.41*	1.39	Yes
Echuca, Australia	0.7	0.75	*0.73*	0.23	No

Sources: the measured CWP values are obtained from Zwart and Bastiaanssen (2004); the simulated CWP values are from this study.

(2004), who summarized the CWP values for wheat, maize and rice measured at different measurement stations in the past 25 years. The simulated CWP of wheat, maize and rice fell within the ranges of measured CWP at 82%, 67% and 64% of the locations, respectively. It needs to be pointed out that the CWP values reported by Zwart and Bastiaanssen represent irrigated agricultural systems. Since rainfed agriculture dominate Oceania and South America, it is not surprising that our simulated CWP values are much lower than the measured values at several sites in Argentina, Brazil and Australia.

There are very few measured CWP values reported for wheat, maize and rice for European countries in Zwart and Bastiaanssen's review paper. The author conducted an additional literature review and found that the CWP values have not been widely reported in Europe. Only a few values can be found in the literature, e.g. CWP of wheat in Italy (Van Hoorn et al., 1993; Katerji et al., 2005) and CWP of maize in France (Marty et al., 1975). Rice is not widely planted in Europe. For maize and wheat, the climatic conditions in many European countries are favorable for their production. In particular, in Western Europe, water is often not an important limiting factor for the growth of maize and wheat. Hence, in many European countries, increasing CWP may not be an issue as urgent as in other dry regions. This is possibly a reason for the few reports on CWP values there. In contrast, in the relatively dry regions (e.g. the North China Plain), water is a very limiting factor for crop growth. In addition, the use of water is competitive among agricultural and other sectors. In this situation, increasing CWP is a very important measure to guarantee high crop yield with limited water uses. The importance of improving CWP will likely result in more frequent reports on the CWP values in the literature in the dry regions such as the North China Plain.

According to the additional literature review, the CWP of wheat ranges from 1.02 to 1.59 kg m^{-3} in Italy (Van Hoorn et al., 1993; Katerji et al., 2005). In this study, the upper limit of simulated CWP of wheat is 1.52 kg m^{-3} in Italy, very close to the upper limit of 1.59 kg m^{-3} in the literature. The lower limit of the simulated CWP is 0.11 kg m^{-3}, and it is much smaller than the reported lower limit (i.e. 1.02 kg m^{-3}) in the literature. The smaller lower limit of this study is expected because this study covers all the cropland of wheat (based on the crop distribution maps), while the reported values are generally measured in specific locations. It is reasonable that our simulated values have a wider range of CWP. The measured CWP of maize is 1.6 kg m^{-3} in France (Marty et al., 1975), much smaller than the simulated national average CWP of maize of 2.19 kg m^{-3}. The measured value was based on experiments conducted in 1975, while our simulations represent the year of 2000. The crop yield of maize more than doubled between 1975 and 2000 (FAO, 2006); hence, much higher CWP values are expected in 2000 compared to those in 1975.

4.3. CWP

Simulation using the GEPIC model showed high spatial variation in the CWP of wheat, maize and rice in the year 2000 (Fig. 4). Table 3 shows the global and regional averages of CWP. The highest CWP of wheat occurs in Europe and Eastern Asia, while the lowest CWP occurs in Oceania and South America, where rainfed wheat dominates. The world average CWP of wheat is 0.952 kg m^{-3}. This number is close to but slightly lower than the mean CWP of wheat reported by Zwart and Bastiaanssen (2004) based on the measured CWP values (i.e. 1.09 kg m^{-3}). It is higher than that reported in Liu et al. (2007b) (i.e. 0.798 kg m^{-3}). Liu et al. do not use a crop distribution map for the simulation. Instead, they calculate the CWP values for all grid cells with dominant land-use of cropland and pasture. This simple treatment may be one reason for the lower value of world average CWP estimated in their study.

The regions with the highest CWP of maize are Western Europe, Eastern Asia, and North America, while the regions with the lowest CWP are Russia and Central Asia, and Eastern Africa. The world average CWP of maize is 1.425 kg m^{-3}. This value is lower than the mean CWP of maize calculated by Zwart and Bastiaanssen (2004) (i.e. 1.80 kg m^{-3}) mainly due to two reasons. First, Zwart and Bastiaanssen estimate the mean CWP of maize in absence of measured CWP values from Eastern Africa, Russia, and Central Asia, where the CWP of maize is generally lower than other regions. Second, Zwart and Bastiaanssen only reported CWP values for irrigated maize; hence, it is not surprising the derived world average CWP is higher.

Regions with the highest CWP of rice are Eastern Asia and North America, while regions with the lowest CWP are Oceania and Southern Africa. The world average CWP of rice is 1.046 kg m^{-3}, which is very close to the mean of CWP of rice calculated by Zwart and Bastiaanssen (2004) (i.e. 1.09 kg m^{-3}). Rice is often planted under irrigated conditions or under rainfed conditions with sufficient precipitation, e.g. in Southeast Asia. In light of this, the water stress of rice should be relatively low. Partly thanks to this, the simulated world average CWP of rice here is close to the one derived based on irrigated rice.

The CWP of maize (a C_4 crop) is generally higher than that of wheat and rice (C_3 crops) (Fig. 3). C_4 crops have roughly twice as high carbon assimilation per unit of transpiration compared with C_3 crops (Rockström, 2003). For a given climatic environment, C_4 crops are likely to be more efficient in assimilating carbon and obtaining higher crop yields with the same amount of water consumption. However, when comparing in different climate zones, it seems that the CWP of wheat in Western Europe is higher than the CWP of maize in many African countries (Fig. 4). CWP is determined not only by the carbon assimilation efficiency, but also the evaporative demand of the atmosphere or vapor pressure deficit. Many studies have reported inverse effects of vapor pressure deficit on CWP (Bierhuizen and Slayter, 1965; Zwart and Bastiaanssen, 2004). Tropical regions have a much higher vapor pressure deficit than temperate regions. The effect of vapor pressure deficit may compensate for or even exceeds the effect of the carbon assimilation efficiency, leading to possibly higher CWP of C_3 crops in temperate zones than that of C_4 crops in tropical zones.

4.4. Sensitivity analysis

The sensitivity index of the five parameters (WA, HI, PHU, PARM3 and PARM42) is first calculated for each grid cell for wheat, maize and rice. The parameter definitions are: WA is the energy conversion to biomass factor; HI is the potential harvest index for a crop under ideal growing conditions; PHU is the potential heat unit accumulation from emergence to maturity; PARM3 is the fraction of maturity when water stress starts reducing the harvest index; and PARM42 affects runoff thus soil water and ET. Then, the most sensitive parameter for CWP is selected for each grid cell and each crop (Fig. 5). The most sensitive parameter appears to vary among grid cells even for the same crop. For wheat, HI is the most sensitive parameter for CWP in 40% of the total grid cells. PARM42

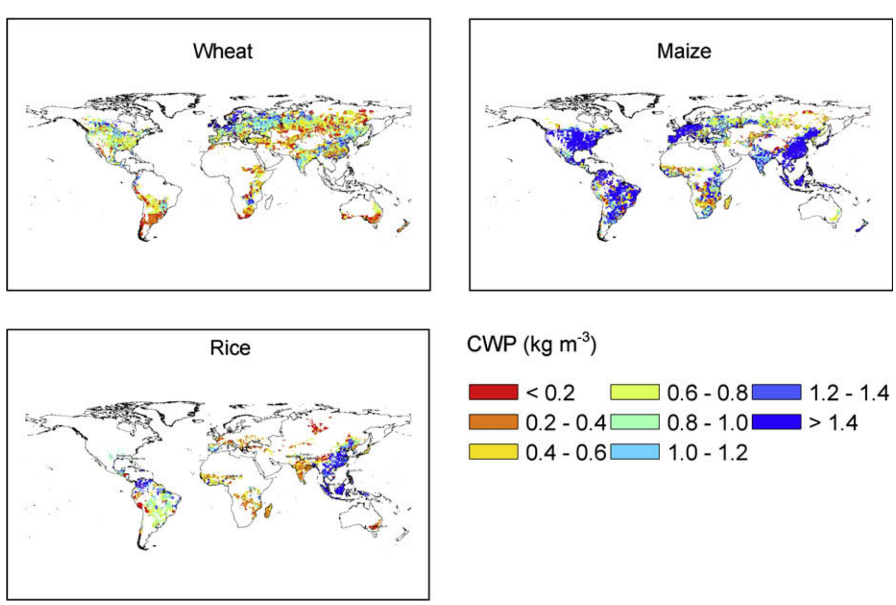

Fig. 4. Spatial distribution of crop water productivity of wheat, maize, and rice.

Table 3
Simulated regional average CWP for wheat, maize and rice

Region[a]	Wheat	Maize	Rice
S-SE-Asia	0.847	1.567	0.945
C-America	0.790	1.297	0.899
N-W-Africa	0.548	0.861	0.778
S-America	0.397	1.441	0.924
Oceania	0.370	1.312	0.227
E-Asia	1.125	1.706	1.345
Russia + C-Asia	0.977	0.693	0.345
W-Asia	0.650	1.391	0.440
N-America	0.901	1.582	1.066
W-Europe	1.256	1.796	0.701
E-Europe	1.102	0.862	0.462
W-Africa	0.691	1.010	0.529
S-Africa	0.404	0.884	0.283
E-Africa	0.578	0.778	0.474
World	0.930	1.425	1.046

[a] The regions are delimitated following that from Yang et al. (2006)

and WA, as the most sensitive parameters, account for 42% (23% for PARM42 and 19% for WA), while PARM3 and PHU together account for the remaining 18%. The CWP of maize is more sensitive to PHU, HI and WA than PARM3 and PARM42 in almost all grid cells. For maize, PHU, HI and WA, as the most sensitive parameters, each accounts for about one-third of the total grid cells (36% for PHU, 34% for HI and 29% for WA), while PARM3 and PARM42 are not the most sensitive parameters in almost all the grid cells. The results are consistent with the findings from Wang et al. (2005a), which concludes that crop yield or crop evapotranspiration is less sensitive to PARM3 and PARM42 for maize. For rice, HI is the most sensitive parameter in 64% of the grid cells, while WA and PHU are the most sensitive in 12% and 23% respectively. PARM3 and PARM42 are the most sensitive parameters in only 1% of the grid cells.

The five input parameters are ranked according to their influence on model output CWP at the continental level (Table 4). For wheat, HI is the most sensitive parameter in all continents. For maize, HI is the most sensitive parameter in Asia, Europe, South America and Oceania, but WA is the most sensitive one in North America and Africa (in both the continents, HI is the second most sensitive parameter). The results also show that, for maize, PARM3 and PARM42 are the least sensitive among the five parameters. For rice, HI and WA are always the first and second most sensitive parameters in all continents, except for Oceania. In Oceania, WA is the most sensitive parameter for CWP, while HI is the second most sensitive one.

Crop yield has a linear relation to HI in the absence of water stress. This relation leads to frequent high sensitivity of CWP to HI. When water stress occurs, the actual harvest index may be much lower than HI which reduces HI sensitivity. Water stress is generally high under rainfed conditions in dry regions. This may be a reason that HI is not the most sensitive parameter for the CWP of maize in Africa. Biomass production is linearly related to WA under non-stressed conditions. However, biomass may be greatly reduced if the crop is stressed, thus reducing WA sensitivity. Crop yield can be sensitive to PHU because PHU sets the time scale (expressed in temperature rather than time). Short PHU values give rapid early growth but less total time to convert energy to biomass. Thus, the sensitivity to PHU depends on several factors with weather being the most important. Since PARM3 sets the time when water stress starts affecting harvest index, crop yield may be affected but the sensitivity is usually not large over a narrow range. PARM42 is

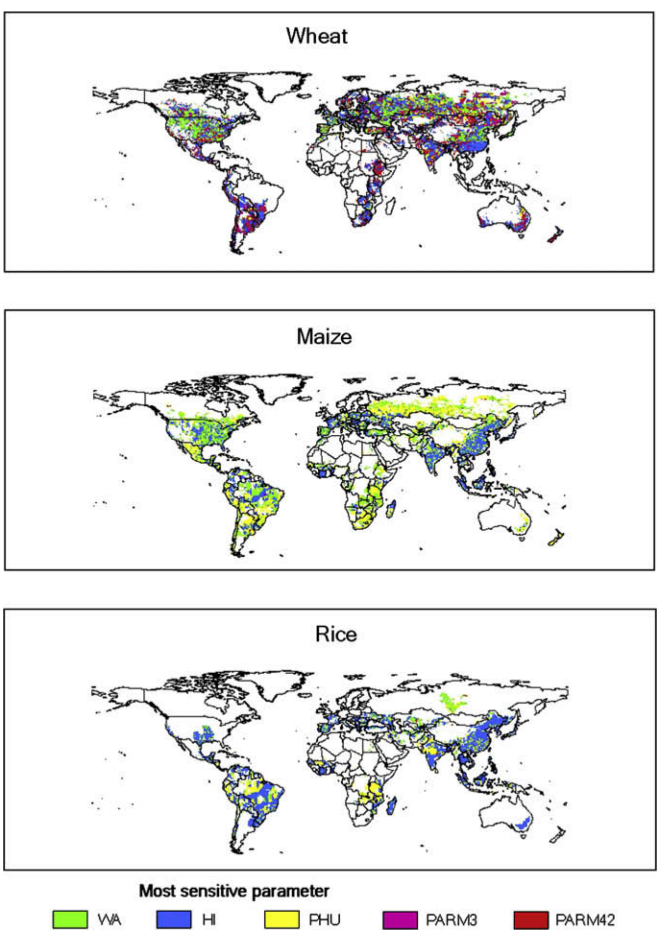

Fig. 5. The most sensitive parameter for wheat, maize and rice.

Table 4
Sensitivities of CWP of wheat, maize and rice to five parameters at the continental level

Continent	Parameter	Wheat		Maize		Rice	
		$\bar{S}_i$	Rank	$\bar{S}_i$	Rank	$\bar{S}_i$	Rank
Asia	WA	0.215	5	0.345	3	0.485	2
	HI	0.995	1	1.012	1	0.997	1
	PHU	0.505	2	0.483	2	0.318	5
	PARM3	0.270	3	0.009	5	0.334	4
	PARM42	0.252	4	0.010	4	0.342	3
North America	WA	0.640	2	0.566	1	0.643	2
	HI	0.736	1	0.510	2	0.972	1
	PHU	0.353	3	0.400	3	0.133	5
	PARM3	0.256	5	0.019	4	0.285	3
	PARM42	0.258	4	0.005	5	0.284	4
Europe	WA	0.222	5	0.560	2	0.771	2
	HI	1.257	1	0.730	1	0.962	1
	PHU	0.962	2	0.364	3	0.173	3
	PARM3	0.706	3	0.050	4	0.112	5
	PARM42	0.682	4	0.010	5	0.120	4
Africa	WA	0.359	5	0.532	1	0.592	2
	HI	1.062	1	0.394	2	0.971	1
	PHU	0.636	2	0.283	3	0.229	3
	PARM3	0.548	3	0.033	4	0.172	5
	PARM42	0.531	4	0.020	5	0.190	4
South America	WA	0.404	2	0.463	3	0.692	2
	HI	0.482	1	0.592	1	0.932	1
	PHU	0.156	3	0.476	2	0.387	3
	PARM3	0.142	4	0.045	4	0.097	5
	PARM42	0.127	5	0.018	5	0.109	4
Oceania	WA	0.595	2	0.169	2	0.790	1
	HI	0.700	1	0.203	1	0.648	2
	PHU	0.210	4	0.126	3	0.291	3
	PARM3	0.205	5	0.009	5	0.098	5
	PARM42	0.217	3	0.039	4	0.102	4

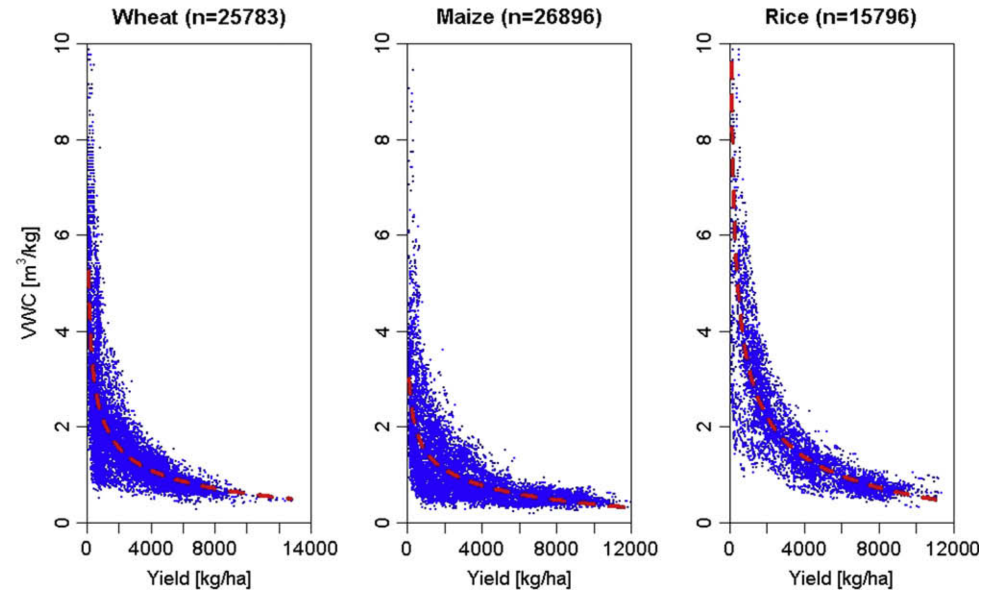

Fig. 6. The relation between VWC and crop yield for all calculated grid cells (total number of n).

non-linearly related to runoff so it affects soil water and thus ET and crop growth. In general, CWP is more sensitive to HI, WA and PHU than PARM3 and PARM42 (Table 4). This is because HI, WA and PHU have a more direct relation to crop yield than PARM3 and PARM42.

4.5. VWC – yield relation

Many authors have reported a linear relationship between crop yield and seasonal ET (Zhang and Oweis, 1999; Huang et al., 2004). The linear ET-yield relationship leads to a constant CWP, or constant VWC. Our results show a non-linear inverse relationship between VWC and yield (Fig. 6). VWC decreases with the increase of crop yield. Obviously, the results do not support the linear ET-yield relationship. ET includes two components: productive crop transpiration (T), which is closely related to crop growth and crop yield, and unproductive soil evaporation (E), which does not contribute to crop growth. In addition, E tends to decrease with a higher yield as a result of shading from increased leaf area (Rockström and Barron, 2007). The linear relationship between ET and crop yield may exist for specific crop growth stages, but this relationship is obviously too simplified for the entire growth period.

The results support the findings suggesting that a linear relationship between yield and ET does not apply, especially for the low yield ranges (e.g. $<6000\ \mathrm{kg\,ha^{-1}}$ for wheat and maize and $<8000\ \mathrm{kg\,ha^{-1}}$ for rice) (see Fig. 6). The non-linear ET-yield relations have been reported in other literature (Falkenmark and Rockström, 2004; Oweis and Hachum, 2006).

Low crop yield may be caused by water stress in sensitive crop growth stages. The water stress reduces crop yield substantially, but may affect ET in other stages less. Hence, ET in the entire growth period will not be reduced linearly with the yield reduction, leading to high VWC values and low CWP values. The VWC-yield relation has important implications for water resources management. The low yield with high VWC (or low CWP) often exists in rainfed conditions in a dry environment, e.g. in many smallholder farms in Africa. When crop yield is low, e.g. <3 kg/ha, supplemental irrigation can significantly improve crop yield, but may only slightly increase seasonal ET. The result is a decreasing VWC, or increasing CWP.

5. Conclusion

GEPIC provides an effective tool to estimate crop water productivity (CWP) on a global scale with high spatial resolutions. The simulation results from the GEPIC model allow broader applications of the database of CWP of wheat, rice and maize. Moreover, the GEPIC model provides a systematic and flexible tool to study crop-water relations on different geographical scales with flexible spatial resolutions. The model allows users to specify the study area and spatial resolution based on their own needs and purposes.

The GEPIC model connects the entire EPIC model with a GIS. Hence, it can go beyond the study of crop-water relations. For instance, the EPIC model also simulates crop growth based on climate parameters such as precipitation and temperature, and nutrient budgets. The GEPIC model thus has the potential to be applied to study the impacts of global climate change on food production, and changes in nutrient dynamics by (increased) agricultural activities. These two areas are emphasized in the ongoing research in our research group.

The accuracy of the GEPIC output depends largely on the quality of the input data. So far, detailed information on crop parameters, crop calendar, and irrigation and fertilizer application for specific crops is not available on a global scale. Assumptions have to be made when using the GEPIC model due to the insufficient input data. The default crop parameters are used for all the regions, but they cannot exactly reflect the local crop characteristics. Access to the more detailed data sets will improve the accuracy of the simulation results. However, as long as the database on these factors is weak, the possibility of reducing uncertainty remains limited. Based on personal experience, the following high-resolution data are needed to fully exploit the potential of GEPIC: irrigation depth, fertilizer application rate, crop calendar, and up-to-date land-use data.

Without high-resolution data on crop yield or CWP, it is difficult to assess the accuracy of the GEPIC model at the grid cell level. Here a qualitative assessment is conducted. The simulation results show that highest yield of wheat occurs in grid cells located in Europe and Eastern Asia, highest yield of maize occurs in grid cells located in Western Europe, Eastern Asia, Southeast Asia, and North America, while highest yield of rice occurs in grid cells located in Eastern Asia, Southeast Asia and Northern part of South America (the results are not presented in the paper). The results are consistent with the statistical yield data of these three crops from FAO (2006). The consistence indicates that the GEPIC model is able to generate a reliable distribution pattern of crop yield at the grid cell level (as well as CWP considering the close relationship between CWP and crop yield).

The comparison between the simulated CWP values in several grid cells with the measured CWP values located within the grid cells (Table 2) shows a general underestimation of CWP in the sites where a large amount of fertilizer is applied, e.g. Xifeng and Luancheng in China, West Bengal and Pantnagar in India and Grand Valley in USA etc. CWP is greatly affected by the application rate of fertilizer, particularly nitrogen fertilizer (Liu et al., 2007b); while in this study, the national average fertilizer application rate is used for all grid cells within a country. This assumption likely leads to underestimation of CWP in the regions with higher fertilizer application rates than the country average, and overestimation of CWP in the regions with lower fertilizer application rates. The assumption of even distribution of fertilizer application rates within a country is a compromise for the absence of the high-resolution fertilizer data, but this assumption is in my opinion the most important source of the simulation errors at the grid cell levels.

Another major source of error is the irrigation map. Although high-resolution irrigation map is available, crop-specific irrigation map is absent. It is assumed that all crops are planted under irrigated conditions when irrigation is equipped. This assumption may be sound for rice and wheat, since both the crops rely heavily on irrigation. However, it may overestimate crop yield as well as CWP of maize in large areas (e.g. in the southern part of China where rainfed maize is often practiced but irrigation is also equipped according to the irrigation map). The lack of crop-specific irrigation map is a constraint for global studies on food production and agricultural water use, and this limitation has been realized by the scientific community. The third major source is the uncertainty of three crop parameters, i.e. potential harvest index, energy-biomass conversion ratio, and potential heat unit, as shown in the sensitivity analysis in this paper. Collection of these parameters with a high spatial resolution seems difficult in the near future in light of the rare report on them. One possible solution is to estimate them with a calibration process, which requires high-resolution data on crop yield. Hence, collection of crop yield data with a high-resolution, or even at a sub-national level, will help reduce the uncertainty caused by these parameters.

The GEPIC model mainly focuses on the natural, physical, and management factors influencing crop production. There is insufficient emphasis on the economic aspects. The GEPIC model considers technological advances as an influencing factor for crop yield, and associates them with the harvest index of individual crops. However, it is not possible to directly study the effects of various food policies and agricultural research investment on crop production. To take these economic issues into account, the economic component in the GEPIC model needs further development.

In this paper, the OAT approach for sensitivity analysis is applied rather mechanistically by adjusting the parameters by $\pm 10\%$. This kind of sensitivity analysis does not take into account the difference between the parameters. The application of this approach is mainly a compromise for the high computation cost of the sampling-based sensitivity analysis. A further improvement in computer speed in the future will make sampling-based sensitivity analysis possible for this study. Currently, a sampling-based sensitivity analysis may only be feasible for a small region, e.g. North China Plain, but it is very challenging on a large scale.

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References

Batjes, N.H., 1995. A Homogenized Soil Data File for Global Environmental Research: a Subset of FAO. Working Paper and Preprint 95/10b. International Soil Reference and Information Center, Wageningen, the Netherlands.

Bierhuizen, J.F., Slayter, R.O., 1965. Effect of atmospheric concentration of water vapour and CO2 in determining transpiration–photosynthesis relationships of cotton leaves. Agricultural Meteorology 2, 259–270.

Brunner, A.C., Park, S.J., Ruecker, G.R., Dikau, R., Vlek, P.L.G., 2004. Catenary soil development influencing erosion susceptibility along a hillslope in Uganda. CATENA 58 (1), 1–22.

Burt, J.E., Hayes, J.T., O'Rourke, P.A., Terjung, W.H., Tod-hunter, P.E., 1981. A parametric crop water use model. Water Resources Research 17, 1095–1108.

Campolongo, F., Cariboni, J., Saltelli, A., 2007. An effective screening design for sensitivity analysis of large models. Environmental Modelling and Software 22 (10), 1509.

Clarke, D., Smith, M., El-Askari, K., 1998. CropWat for Windows: User Guide, Version 4.2. Food and Agriculture Organization of the United Nations, Rome.

Curry, R.B., Peart, R.M., Jones, J.W., Boote, K.J., Allen, L.H., 1990. Simulation as a tool for analyzing crop response to climate change. Transactions of the ASAE 33 (3), 981–990.

Döll, P., Siebert, S., 2000. A digital global map of irrigated areas. ICID Journal 49 (2), 55–66.

Doos, B.R., Shaw, R., 1999. Can we predict the future food production? A sensitivity analysis. Global Environmental Change 9 (4), 261–283.

Dyson, T., 1996. Population and Food: Global Trends and Future Prospects. Routledge, London and New York.

Dyson, T., 1999. World food trends and prospects to 2025. Proceedings of the National Academy of Sciences of the United States of America 96, 5929–5936.

ESRI, 2004. ArcGIS Desktop Developer Guide ArcGIS 9. ESRI Press, Redlands, California.

Evans, L.T., 1998. Feeding the Ten Billion. Plants and Population Growth. Cambridge University Press, Cambridge, UK.

Falkenmark, M., Rockström, J., 2004. Balancing Water for Humans and Nature. Earthscan, London.

FAO, 1990. Soil units of the soil map of the world. In: FAO-UNESCO-ISRIC, Rome, Italy.

FAO, 2006. FAOSTAT: FAO statistical databases. In: Food and Agriculture Organization of the United Nations, Rome.

Fischer, G., van Velthuizen, H.T., Shah, M., Nachtergaele, F.O., 2002. Global Agro-Ecological Assessment for Agriculture in the 21st Century: Methodology and Results. IIASA Research Report RR-02–002. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Frohberg, H., Britz, W., 1994. The World Food Model and an Assessment of the impact of the GATT agreement on Agriculture. Research report, Bonn, Germany.

Gimenez, C., Mitchell, V.J., Lawlor, D.W., 1992. Regulation of photosynthetic rate of 2 sunflower hybrids under water-stress. Plant Physiology 98 (2), 516–524.

Hargreaves, G.H., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture 1, 96–99.

Hijmans, R.J., Guiking-Lens, I.M., van Diepen, C.A., 1994. WOFOST 6.0. (user's guide for the WOFOST 6.0 crop growth simulation model). Technical Document 12 DLO Winand Staring Centre, Wageningen.

Hoekstra, A.Y., Hung, P.Q., 2005. Globalisation of water resources: international virtual water flows in relation to crop trade. Global Environmental Change Part A 15 (1), 45–56.

Holbrook, N.M., Zwieniecki, M.A., 2003. Water gate. Nature 425, 361.

Huang, M., Gallichand, J., Zhong, L., 2004. Water-yield relationships and optimal water management for winter wheat in the Loess Plateau of China. Irrigation Science 23 (2), 47–54.

IBSNAT, 1989. Decision Support System for Agrotechnology Transfer V2.10 (DSSAT V2.10). Honolulu: Department of Agronomy and Soil Science. College of Tropical Agriculture and Human Resources: University of Hawaii, Hawaii.

IFA/IFDC/IPI/PPI/FAO, 2002. Fertilizer Use by Crops, fifth ed. International Fertilizer Industry Association, Rome.

Iglesias, A., Rosenzweig, C., Pereira, D., 2000. Agricultural impacts of climate change in Spain: developing tools for a spatial analysis. Global Environmental Change-Human and Policy Dimensions 10 (1), 69–80.

Ines, A.V.M., Gupta, A.D., Loof, R., 2002. Application of GIS and crop growth models in estimating water productivity. Agricultural Water Management 54 (3), 205–225.

Katerji, N., Van Hoorn, J.W., Hamdy, A., Mastrorilli, M., Nachit, M.M., Oweis, T., 2005. Salt tolerance analysis of chickpea, faba bean and durum wheat varieties: II. Durum wheat. Agricultural Water Management 72 (3), 195.
Lauer, M.J., Boyer, J.S., 1992. Internal CO_2 measured directly in leaves – abscisic-acid and low leaf water potential cause opposing effects. Plant Physiology 98 (4), 1310–1316.
Lawlor, D., 1995. The effects of water deficit on photosynthesis. In: Smirnoff, N. (Ed.), Environment and Plant Metabolism. Flexibility and Acclimation. BIOS Scientific Publishers, Oxford, UK.
Leff, B., Ramankutty, N., Foley, J.A., 2004. Geographic distribution of major crops across the world. Global Biogeochemical Cycles 18 (1), GB1009.
Liu, J., Wiberg, D., Zehnder, A.J.B., Yang, H., 2007a. Modelling the role of irrigation in winter wheat yield, crop water productivity, and production in China. Irrigation Science 26 (1), 21–33.
Liu, J., Williams, J.R., Zehnder, A.J.B., Yang, H., 2007b. GEPIC – modelling wheat yield and crop water productivity with high resolution on a global scale. Agricultural Systems 94 (2), 478–493.
Marty, J.R., Puech, J., Maertens, C., Blanchet, R., 1975. Etude expérimentale de la réponse de quelques grandes cultures à l'irrigation. Comptes Rendus de l'Academie d'Agriculture de France 61, 560–567.
McCuen, R.H., 1973. Role of sensitivity analysis in hydrologic modeling. Journal of Hydrology 18 (1), 37.
Monsi, M., Saeki, T., 1953. Uber den Lichfaktor in den pflanzengesells chaften und seine bedeutung fuer die stoffproduktion. Japanese Journal of Biotechnology 14, 22–52.
Monteith, J.L., 1977. Climate and the efficiency of crop production in Britain. Philosophical Transactions of the Royal Society B 281, 277–294.
Norton, J.P., 2008. Algebraic sensitivity analysis of environmental models. Environmental Modelling and Software 23 (8), 963.
Ort, D.R., Oxborough, K., Wise, R.R., 1994. Depressions of photosynthesis in crops with water defecits. Photoinhibition of Photosynthesis – from Molecular Mechanisms to the Field. In: Bowyer, J., Baker, N.R. (Eds.), Photoinhibition of Photosynthesis. Bios Scientific Publishers, Oxford, UK.
Oweis, T., Hachum, A., 2006. Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. Agricultural Water Management 80, 1–3. 57.
Parry, M., Rosenzweig, C., Iglesias, A., Fischer, G., Livermore, M., 1999. Climate change and world food security: a new assessment. Global Environmental Change 9 (Suppl. 1), S51–S67.
Parton, W.J., McKeown, B., Kirchner, V., Ojima, D.S., 1992. CENTURY Users' Manual. Colorado State University, NREL Publication, Fort Collins, Colorado, USA.
Priya, S., Shibasaki, R., 2001. National spatial crop yield simulation using GIS-based crop production model. Ecological Modelling 136, 2–3. 113.
Quick, W.P., Chaves, M.M., Wendler, R., David, M., Rodrigues, M.L., Passaharinho, J.A., Pereira, J.S., Adcock, M.D., Leegood, R.C., Stitt, M., 1992. The effect of water-stress on photosynthetic carbon metabolism in 4 species grown under field conditions. Plant Cell and Environment 15 (1), 25–35.
Rao, M.N., Waits, D.A., Neilsen, M.L., 2000. A GIS-based modeling approach for implementation of sustainable farm management practices. Environmental Modelling & Software 15 (8), 745–753.
Ritchie, J.T., 1972. A model for predicting evaporation from a row crop with incomplete cover. Water Resources Research 8, 1204–1213.
Rockström, J., 2003. Water for food and nature in drought-prone tropics: vapour shift in rain-fed agriculture. Philosophical Transactions of the Royal Society of London B Biological Sciences 358 (1440), 1997–2009.
Rockström, J., Barron, J., 2007. Water productivity in rainfed systems: overview of challenges and analysis of opportunities in water scarcity prone savannahs. Irrigation Science 25 (3), 299–311.
Rockström, J., Lannerstad, M., Falkenmark, M., 2007. Assessing the water challenge of a new green revolution in developing countries. Proceedings of the National Academy of Sciences of the United States of America 104 (15), 6253–6260.
Rosegrant, M., Cai, X., Cline, S., 2002. World Water and Food to 2025: Dealing with Scarcity. International Food Policy Research Institute, Washington DC.
Rosegrant, M.W., Paisner, M.S., Meijer, S., Witcover, J., 2001. Global Food Projections to 2020 – Emerging Trends and Alternative Futures. International Food Policy Research Institute, Washington, DC.
Rosenzweig, C., Iglesias, A., 1998. The use of crop models for international climate change impact assessment. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht.
Rosenzweig, C., Iglesias, A., Fischer, G., Liu, Y., Baethgen, W., Jones, J.W., 1999. Wheat yield functions for analysis of land-use change in China. Environmental Modeling and Assessment 4, 115–132.
Seckler, D., Amarasinghe, U., Molden, D.J., de Silva, R., Barker, R., 1998. World Water Demand and Supply, 1990 to 2025: Scenarios and Issues. IWMI, Colombo, Sri Lanka.
Stevens, D., Dragicevic, S., Rothley, K., 2007. iCity: a GIS-CA modelling tool for urban planning and decision making. Environmental Modelling & Software 22 (6), 761–773.
Stockle, C.O., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model. European Journal of Agronomy 18 (3–4), 289–307.
Stockle, C.O., Martin, S.A., Campbell, G.S., 1994. Cropsyst, a cropping systems simulation-model – water nitrogen budgets and crop yield. Agricultural Systems 46 (3), 335–359.
Tan, G., Shibasaki, R., 2003. Global estimation of crop productivity and the impacts of global warming by GIS and EPIC integration. Ecological Modelling 168 (3), 357.
Tezara, W., Mitchell, V.J., Driscoll, S.D., Lawlor, D.W., 1999. Water stress inhibits plant photosynthesis by decreasing coupling factor and ATP. Nature 401, 914–917.
Tweeten, L., 1998. Anticipating a tighter global food supply-demand balance in the 21st century. Choices 3, 8–12.
Van Hoorn, J.W., Katerji, N., Hamdy, A., Mastrorilli, M., 1993. Effect of saline water on soil salinity and on water stress, growth, and yield of wheat and potatoes. Agricultural Water Management 23 (3), 247.
Wang, X., He, X., Williams, J.R., Izaurralde, R.C., Atwood, J.D., 2005a. Sensitivity and uncertainty analyses of crop yields and soil organic carbon simulated with EPIC. Transactions of the ASAE 48 (3), 1041–1054.
Wang, X., Youssef, M.A., Skaggs, R.W., Atwood, J.D., Frankenberger, J.R., 2005b. Sensitivity analyses of the nitrogen simulation model, DRAINMOD-N II. Transactions of the American Society of Agricultural Engineers 48 (6), 2205.
Williams, J.R., Jones, C.A., Kiniry, J.R., Spanel, D.A., 1989. The EPIC crop growth model. Transactions of the ASAE 32, 497–511.
Yang, H., Wang, L., Abbaspour, K.C., Zehnder, A.J.B., 2006. Virtual water trade: an assessment of water use efficiency in the international food trade. Hydrology and Earth System Sciences 10, 443–454.
Zhang, H., Oweis, T., 1999. Water-yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. Agricultural Water Management 38 (3), 195–211.
Zwart, S.J., Bastiaanssen, W.G.M., 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agricultural Water Management 69 (2), 115–133.

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Liu, J. and Savenije,H.H.G., 2008. Time to break the silence around virtual-water imports. Nature 453. pp587. doi:10.1038/453587c

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Time to break the silence around virtual-water imports

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Sir

Your News Feature 'More crop per drop' (*Nature* **452**, 273–277; 2008) mentions that China has "unconsciously" turned to 'virtual-water' imports by importing food that requires large amounts of water to produce. Officially, however, the Chinese government continues to advocate self-sufficiency in food because it regards reliance on international food import as a threat to domestic security.

In spite of this strict policy, the annual virtual-water import through food trade increased sharply from 30 billion cubic metres in the 1990s to an average of 71 billion cubic metres a year between 2000 and 2004 (J. Liu *et al*. *Water Int.* **32**,78–90; 2007). The increase is mainly due to the import of water-intensive crops, particularly soya beans. Virtual water is politically silent and economically invisible, and importing it is current practice in China.

China is confronted with water scarcity in several parts of the country, particularly in the North China Plain and the northwestern regions. Several studies have been published on the benefits of incorporating a virtual-water strategy in regional-water management and in food-trade policies for arid regions. These all indicate that importing virtual water into the North China Plain may well be more efficient than transferring 'real' water through the South-to-North Water Transfer Project — a controversial initiative now under construction to divert water from the Yangtze River to northern China (H. Yang and A. Zehnder *Water Resour. Res.* **43,** W12301; 2007).

If a virtual-water strategy had been taken into account in a feasibility study, the decision to invest half-a-billion euros in the transfer scheme might have been different. It would benefit China's development if the political silence around virtual-water transfer were broken and if the issue received more attention in planning water resources.

Liu et al., 2008. China's move to higher-diet hits water security. Nature 454. pp 397. doi:10.1038/454397a

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China's move to higher-meat diet hits water security

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Sir

Your Editorial 'A fresh approach to water' (Nature 452, 253; 2008) points out that the world's looming water crisis is driven by climate change, population growth and economic development. In China, changing food-consumption patterns are the main cause of the worsening water scarcity. If other developing countries follow China's trend towards protein-rich Western diets, the global water shortage will become still more severe.

In China, it takes 2,400–12,600 litres of water to produce a kilogram of meat, whereas a kilogram of cereal needs only 800–1,300 litres (J. Liu and H. H. G. Savenije *Hydrol. Earth Syst. Sci.* **12,** 887–898; 2008). The recent rise in meat consumption has pushed China's annual per capita water requirement for food production up by a factor of 3.4 from 255 cubic metres in 1961 to 860 cubic metres in 2003. Compared with China's population growth by a factor of 1.9 over the same period, this suggests that dietary change is making a high demand on water resources.

China's water requirement for food production is still well below that of many developed countries. The United States, for example, uses 1,820 cubic metres per capita per year. But the steady increase in the amount of meat in Chinese diets is worrying. Consumption already exceeds by 50% the optimal amount recommended by the Chinese Nutrition Society — although discrepancies between rural and urban areas and between eastern and western regions are significant. This diet shift may also have detrimental effects on the population's health, as in developed countries. In general, changes in food-consumption patterns are closely related to affluence, although they are influenced by food preferences as well. Raising public awareness about healthy eating habits could also help to mitigate water scarcity.


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Assessing the value of information for water quality management in the North Sea

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ABSTRACT

Global Earth Observation (GEO) is one of the most important sources of information for environmental resource management and disaster prevention. With budgets for GEO increasingly under pressure, it is becoming important to be able to quantify the returns to informational investments. For this, a clear analytical framework is lacking. By combining Bayesian decision theory with an empirical, stakeholder-oriented approach, this paper attempts to develop such a framework.

The analysis focuses on the use of satellite observations for Dutch water quality management in the North Sea. Dutch water quality management currently relies on information from '*in situ*' measurements but is considering extending and deepening its information base with satellite observations. To estimate returns to additional investments in satellite observation, we analyze the added value of an extended monitoring system for the management of eutrophication, potentially harmful algal blooms and suspended sediment and turbidity in the North Sea. First, we develop a model to make the potential contribution of information to welfare explicit. Second, we use this model to develop a questionnaire and interpret the results.

The results indicate that the expected welfare impact of investing in satellite observation is positive, but that outcomes strongly depend on the accuracy of the information system and the range of informational benefits perceived.

1. Introduction

Information is important for decision-making. Although this seems a rather obvious statement, the value of information for decision-making is seldom addressed. This might not be a problem when sufficient investments in informational services are made, but explicit attention for the value of information is required if too little, or too much, investments in information are made. In the case of Global Earth Observation (GEO), governments and supra-national organizations like the European Space Agency (ESA) and the American National Aeronautics and Space Administration (NASA) have substantially invested in GEO over a long period of time (Peeters and Jolly, 2004). Recently, however, budgets for GEO investment have come under pressure and GEO experts argue that, currently, insufficient investments in GEO are being made (EC, 2007).

GEO information basically involves all observational information concerning the state of the world, including satellite observations and '*in situ*' information. This paper specifically focuses on the added value of satellite-based information.

Generally, satellite-based information extends the geographical and temporal coverage of the information system and supports the development of early warning systems to prevent disasters and avoid damage resulting from, example forest fires, droughts and floods (GEOSS, 2004). Also, it can generate new observations that were not available before. To assess the economic, social and environmental benefits of GEO information, the European commission funded the 3-year GeoBene project (www.geo-bene.eu). This paper presents one of the case studies of this project, an assessment of the economic benefits of satellite-based information for water-quality management in the North Sea.

There are few studies that have actually estimated the value of GEO information. Macauley (2006) and Williamson et al. (2002) discuss the potential benefits of GEO information but do not empirically evaluate any effects. Other papers use rather ad-hoc methods for assessing specific benefits of GEO information, without a more general framework to systematically evaluate effects (see, for example, Isik et al., 2005; Trigg and Roy, 2007; Lybbert et al., 2006; Chen et al., 2004; Kalluri et al., 2003; Kaiser and Pulsipher, 2004). A study that tries to make a comprehensive assessment of the benefits of GEO information is a study commissioned by the ESA to PriceWaterhouseCoopers (PWC, 2006). This study uses stakeholder consultation and expert judgment to evaluate GEO benefits, and concludes that the potential benefits of additional investments in GEO information are large.

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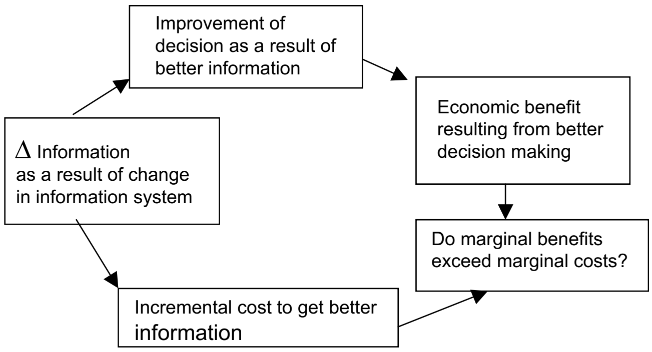

Fig. 1. Assessing the value of information (after Fritz et al., in press).

The problem with the PWC study is, however, that again, an analytical framework is lacking and that the variation in judgments is not represented well. This is crucial for the robustness of stakeholder consultation studies, especially when the uncertainty of the estimates is large (Morgan et al., 2001).

The objective of this paper is to develop a methodologically sound and empirically feasible approach to measuring the economic benefits of GEO information. To focus the analysis we consider the case of Dutch water quality management in the North Sea. At present, water quality in the North Sea is monitored through '*in situ*' measurements. Extending this system with satellite observations would increase the temporal and geographical coverage of water quality monitoring in the North Sea. In addition, it would allow for the development of an early warning system to prevent damages from excessive algal blooms (see the review by Stumpf and Tomlinson, 2005). Also, investing in satellite observation could make a more systematic monitoring of turbidity possible, which could help enforce environmental regulations regarding sea-water clarity around economic activities (construction, sand mining) in the North Sea.

To evaluate the benefits of satellite observation for Dutch water quality management we use an empirical, stakeholder-oriented approach. We develop a methodological framework, based on Bayesian decision theory, evaluating the role of information in the context of decision making under conditions of uncertainty. Based on the work of Schimmelpfennig and Norton (2003) and Morgan et al. (2001) we develop a questionnaire to estimate how investments in satellite-based information are expected to reduce the uncertainty of water quality decision-making. To test the methodology, we select a range of stakeholders involved in water quality management, including experts, policy makers and representatives of interest groups.

The results indicate that the framework of Bayesian decision theory is suitable for assessing the value of information, if respondents have some experience with the use of satellite-based information. In the case of Dutch water quality management, the expected welfare impacts of investments in satellite observation are positive, but outcomes are sensitive to the perceived accuracy of the information system and the range of informational benefits perceived.

In Section 2 we elaborate the conceptual framework and the empirical approach. We then introduce the case study, the use of satellite observations for water quality management in the North Sea. In Section 4 we present the results and in Sections 5 and 6 we discuss the results and conclude.

2. Methods

2.1. Conceptual framework

Assessing the economic value of information basically involves two steps: First, the contribution that information makes to decision-making has to be made explicit. Second, the contribution of better decision making to welfare has to be assessed (Fig. 1).

With regard to the first step, it is important to realize that information can only improve decision-making if decision-making is uncertain. If decision-makers are completely certain about the outcomes of their decision-making, then additional information will have no influence and, hence, will have no significant welfare impact. An exception is when additional information increases the efficiency of the information system. In this case, the incremental costs of additional information are really benefits, for example, when total monitoring costs are reduced.

In the next two paragraphs we elaborate the conceptual framework for assessing the value of information, using the economic literature on decision-making under uncertainty. In this literature, the contribution of information to decision-making and the contribution of decision-making to welfare are jointly addressed. The potential impact of informational investments on monitoring costs is not further elaborated. However, when considering the welfare impacts of investments in Dutch water quality monitoring, both the costs and benefits of the investment will be addressed.

2.1.1. Decision making under uncertainty

In their seminal paper on the economics of information, Hirshleifer and Riley (1979) provide a theoretical framework for analyzing the role of information when decision-makers are uncertain about 'the state of the world' (event uncertainty). In a certain world, economic theory predicts that a rational decision-maker will choose the action with the highest utility. If outcomes are uncertain, decision-makers base their decisions on the *expected* utility of the outcomes instead. This expected utility depends on the perceived probability of the different 'states of the world', or the expected probability that a certain outcome will be reached[1].

Table 1 presents the decision problem for two potential actions ($x = 1{,}2$) and two possible states of the world ($s = 1{,}2$). As Hirshleifer and Riley (1979) express it: the decision-maker chooses among *actions*, while Nature may be metaphorically said to choose among *states*. The consequences (or outcomes), $c_{x,s}$, of the actions, differ depending on the 'state of the world'.

Formally, the expected utility of action x can be expressed as,

$$u(x,\pi_s) \equiv \pi_1 v(c_{x1}) + .. + \pi_S v(c_{xS}) \equiv \sum_{s=1}^{S} \pi_s v(c_{xs}) \quad (1)$$

with π_s the perceived probability of state s, c_{xs} the consequence (or outcome) associated with action x in state s, v the utility of the outcome of the actions given the different states of the world, and S the number of possible states of the world.

Without information about the probability of alternative 'states of the world', a decision-maker must act upon his own (prior) beliefs. If the decision-maker is very uncertain about 'the states of the world' and these states have a large impact on the consequences of alternative actions, it might be a good idea to seek additional information about the likelihoods of the potential 'states of the world' before taking action. Whether a decision-maker is willing to invest in acquiring information will, depend on the extent to which information is expected to reduce the uncertainty of his or her decision-making. It is important to note here that the decision-maker is taken to be a private actor. When discussing water quality management, this is, clearly, not the case. Still, the

[1] We consider expected utilities, and not expected values, since decision-makers might have variable risk preferences. Although in the case study we only consider expected values, the methodological framework should be general enough to include risk preferences in the analysis as well.

Table 1
Decision making under uncertainty

		States		
		$s=1$	$s=2$	Utility of the acts
Actions	$x=1$	c_{11}	c_{12}	u_1
	$x=2$	c_{21}	c_{22}	u_2
	Beliefs as to the state	π_1	π_2	

theoretical framework of Hirshleifer and Riley (1979) is applicable, if we assume that the (public) decision-maker maximizes social, instead of individual, returns. We will come back to this assumption when elaborating our empirical approach.

2.1.2. The value of information

Using the framework developed by Hirshleifer and Riley (1979) requires a couple of steps. First, the impact of an informational message on decision-making needs to be assessed. This depends on the extent to which the decision-maker uses the information to update his beliefs regarding the 'state of the world'. A formal way of expressing the process of belief updating is reflected in the well-known Bayes theorem[2]:

$$\pi_{s,m} = \Pr(s|m) = \frac{\Pr(m|s)\Pr(s)}{\Pr(m)} = \frac{q_{m,s}\pi_s}{q_m} \tag{2}$$

with $\pi_{s,m}$ the posterior probability, or the updated belief, π_s the prior probability, or the belief before the additional information, $q_{m,s}$ the conditional probability of receiving message m given state s (the likelihood of receiving message m given state s), and q_m the unconditional probability of receiving informational message m. The unconditional probability of receiving message m is related to the conditional probabilities (of receiving message m in state s) by:

$$q_m = \sum_{s=1}^{S} q_{m,s}\pi_s \tag{3}$$

hence, whether an informational message succeeds in making decision-makers change their belief function depends upon the decision-makers prior belief regarding the possible 'states of the world' and the perceived accuracy of the informational message, or the likelihood of receiving message m given state s.

Subsequently, with the 'updated beliefs' the decision-maker might choose a different action than what he would have chosen with his prior beliefs. The 'value' of message m is simply the difference between the utilities of the actions that is chosen given message m (x_m) and the action that would have been chosen without additional information (x_0):

$$\Delta_m = u(x_m, \pi_{s,m}) - u(x_0, \pi_{s,m}) \tag{4}$$

Then, since we do not know in advance which message the information service will produce, the expected value of the information is the expected difference in utilities of actions given the likelihoods of receiving messages m (q_m):

$$\Delta(\mu) = E(\Delta_m) = \sum_m q_m [u(x_m, \pi_{s,m}) - u(x_o, \pi_{s,m})] \tag{5}$$

$\Delta(\mu)$ is the expected utility of the new information, and can thus be used as an indicator of the value of this information, or the decision-maker's maximum willingness to pay. A rational decision-maker would invest in informational services if his or her willingness to pay (reflecting the societal willingness-to-pay) exceeds the cost of purchase.

In fact, there are three factors that determine the value of information (Hirshleifer and Riley, 1979). First, it depends on the confidence decision-makers have in their beliefs. The more confident the decision-maker is about his expectation regarding the possible state of the world, or the tighter the decision-makers' probability distribution function, the less likely the decision-maker is to invest in information or change his beliefs. Second, it depends on the extent to which the decision-maker expects the information to be true. As in statistical significance testing, an informational message can be false in two ways: the message can incorrectly reject the 'true' state, and it can fail to reject the 'false' state. In decision theory, the former error is called a Type I error and the latter error is called a Type II error. If the perceived errors are large, the value of the information will, clearly, be less. Third, it depends upon the content of the information: the more surprising the informational message, or the larger the difference with the existing belief, the greater the likelihood that the prior belief will be updated (Hirshleifer and Riley, 1979; Lybbert et al., 2006).

2.1.3. Assessing the value of GEO information

Although Bayes' rule has been widely applied in theoretical work analyzing decision-making under conditions of uncertainty (see, for example, Yokota and Thompson (2004)) few studies have actually tried to empirically estimate the prior and posterior probabilities involved. One of the few studies that have attempted to empirically estimate prior and posterior probabilities is the study by Schimmelpfennig and Norton (2003). To evaluate the value of agricultural economics research, Schimmelpfennig and Norton asked senior policy makers about their perceptions of the payoffs, measured in terms of economic surplus estimates, $\nu(c_{xs})$, prior probabilities, π_s, and the likelihoods of new research producing "true" messages, $q_{m,s}$. On the basis of this information, they were able to calculate the value of agricultural economics research in a number of case studies, such as a crop insurance program and a food safety program.

This paper builds on the approach of Schimmelpfennig and Norton, using stakeholder consultation to estimate the extent to which decision-makers actually use GEO information to update their beliefs. In Section 2.2 we further elaborate our approach.

2.2. The empirical approach

Although Schimmelpfennig and Norton (2003) suggest that it is sufficient to consult one or two key decision-makers to estimate prior and posterior belief functions, there are two reasons why we believe that it is important to consult a wider range. First, public decision-making often involves more than one actor and by capturing the perceptions of several key actors a more representative estimate of the value of information can be made[3]. Second, given the large uncertainties surrounding the estimation of the value of information, involving a larger number of respondents might help increase the robustness of the results. Hence, in line with the broader literature on stakeholder elicitation (see, for example, Morgan et al., 2001) we decided to consult a wider range of stakeholders and use the variance of the respondents' answers to analyze the robustness of our results.

[2] There is actually more work on Bayesian decision theory in environmental management, even if few of those deal with the value of information directly (see, for example, Ellison, 1996; Varis and Kuikka, 1999).

[3] Schimmelpfennig and Norton (2003) suggest that if decision-making is strategic, or if more than one decision-making center is involved, explicit attention should be paid to the political weight of the different decision-making centers. In the case of Dutch water quality management, decision-making is strongly consensus-based. Hence, we do not explicitly account for the political weight of the different decision-making centers but instead assume that in the decision-making process the views and interests of the different actors are accounted for.

For the stakeholder consultation, we developed a questionnaire based on Bayesian decision theory. The main aim of the questionnaire was to elicit stakeholder perceptions regarding the impact of satellite observations on the effectiveness of water quality monitoring in the North Sea. We asked respondents to evaluate three cases: the value of GEO information for the management of (a) potentially harmful algal blooms, (b) eutrophication and (c) seawater turbidity and suspended sediments. We asked respondents to compare the existing information system of mainly '*in situ*' measurements with a situation in which use is made of additional satellite observations as well, illustrating the examples with images and explanatory text (see Fig. 2).

We asked respondents to quantify their answers when estimating the extent to which they expected satellite-based information would reduce the uncertainty of decision-making. In addition, we asked some qualitative questions about the perceived value of information, the occurrence of certain events and the extent to which respondents expected that the demand for satellite observation information would increase due to, for example, the future implementation of the European Marine Strategy or other expected developments and trends.

We tried to get a representative spread of decision-makers and experts concerned with marine water quality management in the North Sea. In the total number of 23 respondents, we included 8 policy makers, 7 water managers, 4 researchers and 4 representatives of interest groups. Respondents were selected on the basis of their expertise and experience with water quality monitoring in the North Sea. In addition, we tried to get representatives from each of the parties involved in Dutch water quality management. Also, we suggested in the e-mail accompanying the questionnaire that respondents were free to forward the questionnaire to their colleagues or other potential candidates.

By consulting a wide range of stakeholders, we hoped to not only gain insight into the distribution of answers, but to test the empirical feasibility of the methodological framework as well. Better understanding of the factors determining whether decision-makers can quantify the contribution of information can help further develop the empirical approach. Clearly, with a population of only 23 subjects, it is impossible to reach statistically robust results, but given the research objective, it seemed important to test the empirical feasibility of the approach as well.

We tested the questionnaire internally and externally by having two senior decision-makers answer the questions beforehand. Before sending the questionnaire off, we contacted all selected respondents to explain the project and ask for their collaboration. We promised respondents that their answers would be dealt with anonymously and that we would share the results. Of the 23 questionnaires we distributed, we received 19 copies back (83%). Of these 19 responses, 14 answered the full questionnaire while 5 left most of the questions blank. Only 10 respondents (52%) responded to most questions quantitatively. Before we analyze the results, in Section 3 we first introduce the case study.

3. Description of the case study

The North Sea is one of the world's major shelf seas and one of the major fish-producing ecosystems in the world. The marine ecosystems in the Dutch part of the North Sea are under intense anthropogenic pressure from fishing, nitrogen input (from air and rivers), recreational use and habitat loss. The main problem is eutrophication, or an excess of nutrients in the marine ecosystem (Vermaat et al., 2004). Eutrophication results in changes in the marine ecosystem, causing biological, chemical and physical changes in the structure of flora and fauna. In addition, and probably as a result of eutrophication, the intensity and frequency of excessive growth of micro-algae has increased over the last decennia (Cadée and Hegeman, 2002; Glibert et al., 2005). These algal blooms can result in the release of substances that are toxic

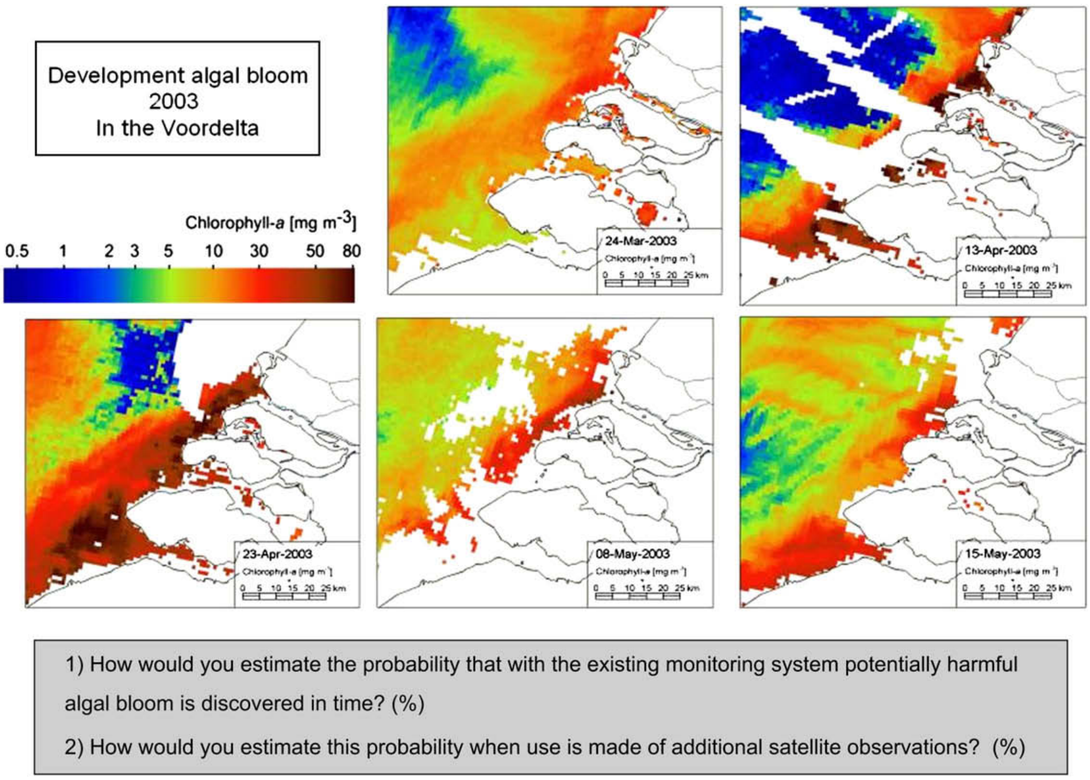

Fig. 2. Example of questionnaire questions.

both to man and to other marine life. When these blooms decay, it may cause benthic anoxia, leading to the seabed being devoid of much of its life (EEA, 2003). One of the most important economic damages resulting from excessive algal blooms is loss of shellfish production and dying fish.

To inform water managers and policy makers about the spread and intensity of eutrophication and to warn about the possibility of potentially harmful algal blooms, the Dutch Ministry of Transport and Public Works maintains a monitoring programme at 19 marine stations in the Dutch part of the North Sea (www.waterbase.nl) taking bi-weekly water samples. At present, the ministry is considering extending this system of water quality monitoring with satellite observations regarding chlorophyll-a concentrations and suspended sediment (Roberti and Zeeberg, 2007). Chlorophyll-a is the main light-harvesting pigment of algae and is therefore a proxy for the algal biomass. Suspended sediment is the main source of turbidity, which determines to a large extent the underwater light climate in the North Sea (RIKZ, 2002).

To contribute to the discussion regarding the use of satellite observations for water quality monitoring in the North Sea, we initially wanted to consider three case studies; eutrophication, excessive algal blooms and suspended matter. However, since we could only make an estimate of the economic pay-offs associated with an early warning system for excessive algal blooms, we had to concentrate on this one case study instead.

In the case of eutrophication, estimating economic pay-offs was difficult because more than 85% of the nutrients come from poorly controllable sources, like historical stocks of phosphates and nitrates and atmospheric deposition. Hence, better information about the geographical and temporal spread of chlorophyll-a hardly allows for better-targeted interventions [4]. Similarly, the economic pay-off associated with improved monitoring of seawater clarity and turbidity was difficult to assess. Not only do large uncertainties exist as to the impact of suspended sediments on ecosystem functioning, it is unclear to what extent information about suspended sediments can be used to improve seawater clarity and avoid damages in the long run (Pasterkamp and Vermaat, 2004).

Fortunately, there are clear pay-offs associated with the prevention of economic damages resulting from excessive algal blooms. In 2001, excessive algal blooms caused a loss of approximately 20 million euro to the Dutch mussel cultivation sector (Peperzak, 2003). If early warning information would have been available, this loss could have been avoided by preventively relocating mussel cultivation plots at 10% of the damage costs (Woerd et al., 2005). In fact, in 2006 an early warning system became operational for the near-real time early detection and forecasting of algal blooms in Dutch coastal waters, using a combination of field data, satellite observations and hydrodynamic- and biological modeling (Woerd et al., 2005, submitted for publication). The system can detect rapid rises in chlorophyll-a levels during bloom formation. On the basis of these observations a transport model makes predictions about the transport of the bloom, 5 days ahead. In case of a perfect system, this would allow the mussel farmer sufficient time to take adaptive measures.

Also, we estimated the impact of GEO information on water quality monitoring costs. Generally, it is expected that satellite observation can substantially reduce monitoring costs (Roberti and Zeeberg, 2007). In the case of eutrophication, Hakvoort (2006) estimates a cost reduction of approximately 40%, or 2 million euro per year. In this estimate, the capital costs of satellite observation are not included. When also accounting for the capital costs of satellite observation, annual costs are approximately 2.5 million per year (personal communication of Dutch aeronautics and space institute, NIVR). Based on these crude estimates, the prevention of economic damage from excessive algal blooms would need to generate an annual benefit of at least 500,000 euro to make GEO investments economically efficient. This figure does not include the operational costs of developing and maintaining an early warning system, but from a (confidential) cost-benefit analysis carried out in the development phase of the algal blooms early warning service, we know that the operational costs are comparatively small, i.e. less than 10% (Woerd et al., 2005).

4. Results

4.1. The value of GEO information

The main results of the questionnaire are presented in Table 2.

The results show that, on average, respondents expect that satellite observations will improve water quality monitoring in the North Sea. The expected improvement is largest in the case of suspended sediments and the related turbidity, because the present monitoring system only covers certain locations, and gives very limited insight into the distribution of seawater clarity in the North Sea (RIKZ, 2002). For eutrophication the opposite holds, with well-functioning water monitoring system in place and good insight in the relation between the sources and effects (see, however, McQuatters-Gollop et al., 2007). In the case of potentially harmful algal blooms, currently no early warning system exists, but information about chlorophyll-a levels can be used to help predict excessive algal blooms.

Interestingly, the range of answers is especially large for the present monitoring of excessive algal blooms and the potential satellite-based monitoring of suspended sediment. This can be explained by the fact that: (a) opinions differ as to the need for an early warning system regarding algal blooms[5] and (b) the fact that the idea of having a satellite-based information system for the monitoring of suspended sediment remains relatively unexplored. In fact, several respondents indicated not being very confident about their answers regarding the monitoring of suspended sediment as they knew relatively little about this technique.

Still, the range in answers is substantial and the number of those able to quantify their answers relatively low (10 out of 19). If we divide respondents on the basis of their (self-reported) expertise and professional affiliation, we end up with four respondent groups (4–6 persons per group): (1) policy makers-general, (2) policy makers-experts (3) researchers and (4) water managers, practical. Interestingly, in the last group respondents were not able to quantify any answers. The main explanation for this seems to be that these respondents indicated knowing little about satellite-based information and having difficulties to quantitatively assess the contribution of information to decision-making.

In Fig. 3 we present the results of the first three groups[6]. Since the results indicated that four respondents might have strategically answered the questionnaire, we present two results per group: with and without the outliers (= strategic responses). Outliers were

[4] Considering the uncertainties that exist with regard to the main drivers of eutrophication, in the longer run this situation might change. For example, there is an ongoing debate about the relative importance of seawater temperature versus nutrient inflow (see, for example, McQuatters-Gollop et al., 2007). If this changes the understanding of eutrophication processes, it could change the value of observational information regarding chlorophyll-a. At present, measures like the removal of saturated soils might be an option, but the costs of these measures are such that they are generally not considered being economically feasible.

[5] For example, local fishermen suggested that they can actually see excessive algal blooms coming by looking at the sea. However, this reaction seems at least partly inspired by strategic reasoning, as fishermen do not want to contribute to the costs (they do want the government to compensate their losses, however).

[6] And, obviously, we only present figures of the respondents that were able to quantify their answers.

Table 2
The added value of satellite observations for water quality monitoring in the North Sea

	Eutrophication ($n = 13$)		Potentially harmful algal blooms ($n = 10$)		Suspended sediments ($n = 10$)	
	Present (%)	Present + GEO (%)	Present (%)	Present + GEO (%)	Present (%)	Present + GEO (%)
Average expectation of water quality being well monitored[a]	63	75	50	73	26	69
Range in answers	50–100	80–100	10–90	50–100	10–50	20–90

[a] Median values are, respectively, 60% and 80%, 50% and 73% and 25% and 70%.

defined on the basis of their professional affiliation: in the first two groups, two respondents seemed to strategically underestimate the contribution of satellite-based information, because of their strong affiliation with the current monitoring system. In the expert group, the two representatives of interest groups seemed to have overestimated the benefits for strategic reasons as well.

Interestingly, general policy makers seem to expect most from investments in satellite observation, whereas the water managers responsible for water quality monitoring judge the remaining uncertainties to be relatively high. Experts are most optimistic about the uncertainties associated with the information system, but they regard the added value of satellite observations to be relatively small. Ideally, the answers of the different respondents would be weighted for their impact on water quality decision-making. Roughly speaking, water policy makers are most likely to play a decisive role in investment-related decision-making, whereas the role of outside experts is likely to be small. However, since we don't have information to weight respondent perceptions, we take the average values, as reported in Table 2, to reflect the expected likelihood that satellite observations accurately predict harmful algal blooms on time, the perceived likelihood being on average 75% (the Type I error is therefore 25%).

In addition to the likelihood that the information system is accurate in predicting potentially harmful algal blooms, we also need to know the probability that the system predicts excessive algal blooms when the threat of economic damage is nil (Type II error). Unfortunately, questions asking respondents about the perceived Type II accuracy of the monitoring system were hardly answered. Hence, we had to assume a Type II error on the basis of expert judgment instead. We assume the accuracy of the early warning system to be 90%, reflecting a 10% probability (= Type II error) that predictions in satellite observations near bloom detection threshold levels are too high (Woerd et al., 2005). Since the system has only been operational for a limited amount of time, a more robust estimate of the Type II error can, at present, not be made. Hence, we will explicitly account for different Type II errors when assessing the robustness of our results.

Now, to assess the value of early warning information, we assume a decision-making process in which the water quality manager decides weekly whether to relocate the fishing nets (Action $x1$) or to do nothing (Action $x2$). The time period considered is a week since the information system makes bi-weekly predications and as soon as a bloom is observed, within 24 h of the actual satellite overpass, hydrodynamic models can predict algal bloom transport 5 days ahead. Also, we assume decision-makers minimally need a week to relocate mussel stocks (see also Songhui et al., 2000 and Fernández et al., 2003). In the questionnaire, respondents unanimously indicated that they expected that potentially harmful algal blooms, like the one in 2001, would take place every 5 years. Since potentially harmful algal blooms are only possible during a period of 10 weeks, or 2 months, a year, there is a perceived probability of 2% per week of potentially harmful algal blooms taking place (Reid et al., 1990). Hence, the prior expected probability of potentially harmful algal blooms is estimated to be 2%. In Table 3 we illustrate the decision-making problem using the framework of Bayesian decision theory.

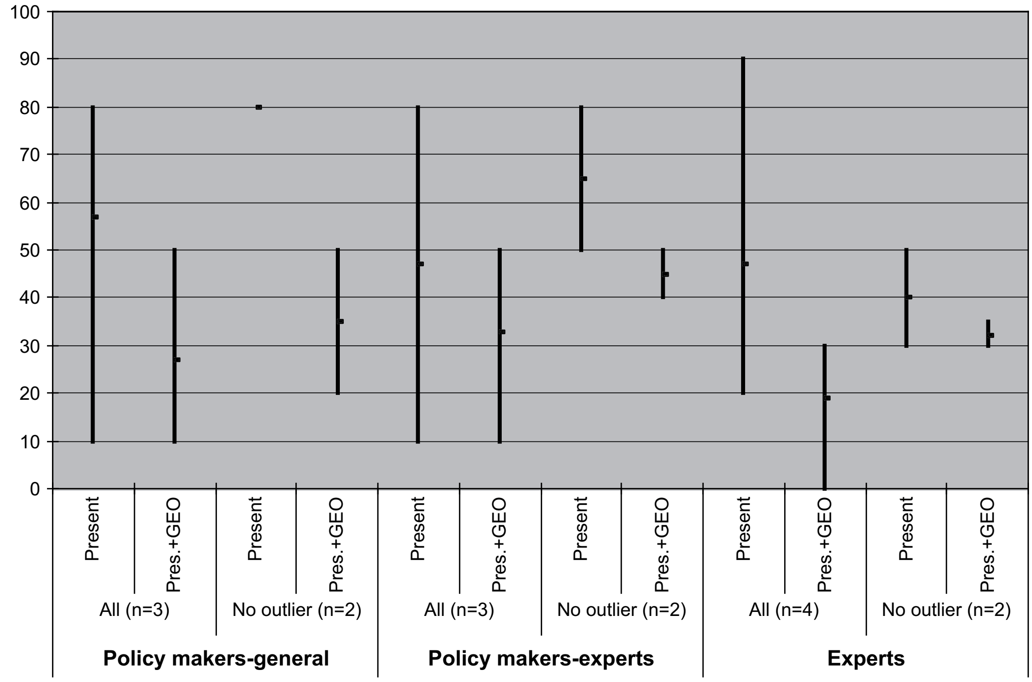

Fig. 3. Perceived uncertainties in the monitoring of potentially harmful algal blooms.

Table 3
The decision-making matrix for assessing the value of information

States (s)	Actions (x) (in million euro/week)*		Priors (π_s)	Likelihoods ($q_{m,s}$)		Joint probabilities ($\pi_s q_{m,s}$)	
	$x1$: relocate fishing nets	x2: do nothing	π_s	$m1$: “Danger!”	$m2$: “No panic”	$m1$	$m2$
S1: harmful algal bloom	−2	−20	0.02	0.75	0.25	0.015	0.005
S2: non-harmful algal bloom	−2	0	0.98	0.10	0.90	0.098	0.882
$u(x, \pi_s) = \Sigma\pi_s c_{xs}$	−2	−0.4		Message probability ($q_m = \Sigma q_{m,s}\pi_s$)		0.113	0.887
$u(x_0, \pi_s) = \text{ma} \times u(x, \pi_s)$		−0.4		Posteriors ($\pi_{s,m} = q_{m,s}\pi_s/q_m$)	$s1$	0.133	0.006
					$s2$	0.867	0.994
				Expected surplus $u(x, \pi_{s,m}) = \Sigma\pi_{s,m}c_{xs}$	$x1$	−2.000	−2.000
					$x2$	−2.655	−0.113
				$u(x_m, \pi_{s,m}) = \max u(x, \pi_{s,m})$		−2.000	−0.113
				$\Delta(\mu) = \Sigma q_m[u(x_m, \pi_{s,m}) - u(x_0, \pi_{s,m})]$		0.074	

*Source: Peperzak (2003) and Woerd et al. (2005).

Table 3 shows that without the early warning system, a rational water quality manager would do nothing because the expected utility of Action $x2$ (–€0.4) is greater than that of Action $x1$ (–€2.0). With the information system in place, the water quality manager can update his prior beliefs regarding the probabilities of potentially harmful algal blooms according to Eq. (2). (see also the posteriors in Table 3). With these updated beliefs, the rational water quality manager will now relocate fishing nets (Action $x1$) when the information system predicts potentially harmful algal blooms (“danger!”; $u(x1) = -2 > u(x2) = -2.655$) and will do nothing when the information system gives no warning (“No panic”; $u(x1) = -2 < u(x2) = -0.113$)). The value of the information system ($\Delta(\mu)$) can now be calculated with Eq. (5).

As the results in Table 3 show, the value of information ($\Delta(\mu)$) is estimated to be €0.074 million (or €74,000) per week. Since the costs of the new information system are only €50,000[7] per week, the benefits of investing in satellite observations exceed costs by almost €24,000 per week suggesting a social rate of return of 48%. Clearly, with large uncertainties surrounding the likelihood estimates, the robustness of these results needs to be assessed. This will be the subject of the next paragraph.

4.2. Robustness of the results

There are two factors that are likely to significantly influence our results. First, our estimate of the probability that the information system would wrongly predict potentially harmful algal blooms (Type II error) is based on expert judgment. The expert consulted indicated that little is known about Type II errors and that the actual uncertainties might be higher. If we assume, for example, that the probability of a Type II error is 20%, then the value of information becomes nil. In fact, given a Type I error of 25%, once the probability that Type II error exceeds 13%, the value of information becomes nil. Fig. 4 presents the value of information as a function of Type I and Type II errors, ranging from 50% to 0% and from 30% to 0%, respectively. The x-axis (the base) depicts Type I errors, the y-axis (depth) depicts Type II errors and the z-axis (height) depicts the value of information in euro million. Completely accurate information (zero errors) would have a value of €0.37 million. The value of information decreases sharply as Type II errors increase and it also decreases (but somewhat less sharply) as Type I errors increase. In our central estimate, with a Type I error of 25% and a Type II error of 10%, the value of information is €0.074 million.

[7] The costs per week (€50,000) are calculated as annual costs (€500,000) divided by 10 weeks of potential algal bloom. Again, the operational costs of the early warning system are not included, but they are relatively low.

Second, considering the variance in respondent answers, the results might change too. Accounting for the range in respondent perceptions the 95% confidence interval for the value of information ranges from 34,000 to 103,000 euro a week. Given that the estimate of satellite observations reducing existing monitoring costs with 2 million euro per year is expected to overestimate the actual benefits, the benchmark of 50,000 euro per week is probably the lower bound. Given the variance in responses, the expected probability that this benchmark is reached is approximately 75%. Hence, there is a 75% probability that investments in satellite observation are welfare enhancing in the case of Dutch water quality management in the North Sea. Still, if the Type II accuracy of information is less than 90%, this is no longer the case.

5. Discussion

The results of the analysis indicate that in the case of Dutch water quality management there is a 75% probability that investments in additional satellite observation are welfare enhancing. However, the results strongly depend on whether the accuracy of the information system is sufficiently high. Most studies assessing the value of information do not pay attention to the accuracy of the information system or the Type-I and Type-II errors involved. This basically means that these studies cannot present a robust estimate of the value of information, since the accuracy of the evaluated information system might be relatively low. Also, paying attention

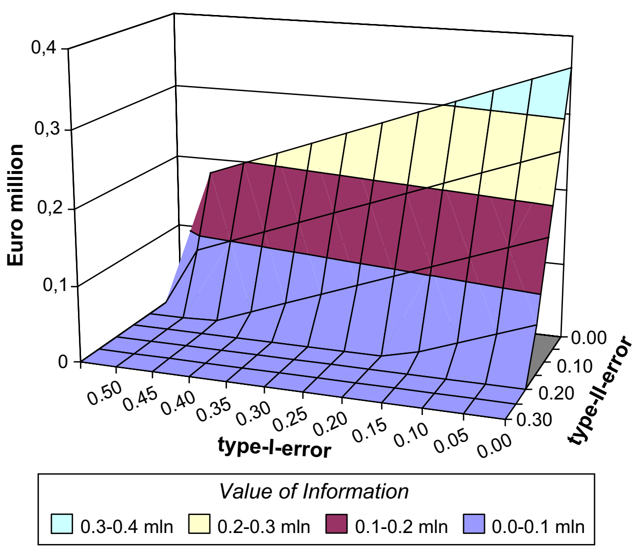

Fig. 4. The value of information as a function of the sizes of Type I and Type II errors.

to the perceived accuracy of the information system provides important information for information system developers, who tend to pay little attention to the impact false predictions might have. By making the economic value of improving information system accuracy explicit, investments in system improvement can be better targeted and returns to investment can be improved.

In addition, this paper has shown that Bayesian decision theory offers a suitable framework for assessing the economic value of information. By combining Bayesian decision theory with stakeholder consultation, it becomes possible to evaluate the added value of informational investments. However, the analysis also indicated that using Bayesian decision theory requires a high level of expertise and awareness of the respondents: respondents with little background in satellite-based information systems were not able to answer questions in a quantitative way.

This is actually an important outcome, since it indicates that the value of information depends on awareness levels as well. The wide range in respondent answers also indicates that the uncertainties surrounding the estimates are large. Apart from differences in understanding the potential of satellite-based observation systems, respondents differ in their understanding of the potential uses of satellite-based observations as well. Clearly, observations that help a complex model reduce the uncertainty of its predictions have a higher economic value than observations for which no scientific models yet exist. This also became apparent from the case study analysis, respondents being less able to estimate the added value of turbidity monitoring since the potential uses of these kinds of observations are still largely unclear. All in all, the large uncertainties surrounding value of information estimates and the fact that estimates also depend on awareness levels seem to underline the importance of including several decision-makers in the consultation. Although this might not make it possible to present statistically robust estimate of the value of information, accounting for the variance in respondent answers does allow for a more robust representation of results.

Finally, there are two factors that have not been explicitly addressed in this paper, but that might require further elaboration in the work to come. First, there are several psychological reasons why people might not use (new) information to update their beliefs (Rabin, 1998). Although by consulting experts the biases resulting from such non-rational behavior might be somewhat reduced, further research is needed to assess the potential impact of these effects. Second, in the analysis of this paper we did not explicitly account for political factors, assuming that the consensus-oriented approach of Dutch water management would include the perceptions of all stakeholders in the final decision made. However, one respondent remarked that the department responsible for the monitoring of water quality in the North Sea is not responsible for damages caused to the mussel sector and that, hence, water quality managers have no incentive to invest in early warning systems at all. This is a good example of how the organization of resource management and information access matters in assessing the value of information. It is also an indication that the value of information generated is only a potential value and that the actual value will depend upon political factors as well.

6. Conclusion

We started this paper by noting that although there seems to be an increasing demand for studies estimating the value of information, a theoretically sound and empirically feasible approach seem to be lacking. This paper has shown that a combination of Bayesian decision theory and expert consultation can offer a suitable approach. The approach seems especially promising as it links the value of information to the accuracy of the information system. This is important because this: (a) increases outcome robustness and (b) provides information that can help improve the accuracy of the information system itself.

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References

Cadée, G.C., Hegeman, J., 2002. Phytoplankton in the Marsdiep at the end of the 20th century; 30 years monitoring biomass, primary production, and Phaeocystis blooms. Journal of Sea Research 48, 97–110.
Chen, Q., Zhang, Y., Ekroos, A., Hallikainen, M., 2004. The role of remote sensing technology in the EU water framework directive. Environmental Science & Policy 7, 267–276.
Ellison, A.M., 1996. An introduction to Bayesian inference for ecological research and environmental decision-making. Ecological Applications 6 (4), 1036–1046.
European Commission, 2007. European Space Policy. Communication from the commission to the council and the European Parliament, COM 212, Brussels.
European Environmental Agency, 2003. Testing of Indicators for the Marine and Coastal Environment in Europe. EEA, Copenhagen, ISBN 92-9167-508-3. Technical report 86.
Fernández, M.L., Shumway, S., Blanco, J., 2003. Management of shellfish resources. In: Hallegraeff, G.M., Anderson, D.M., Cembella, A.D. (Eds.), Manual on Harmful Marine Microalgae. UNESCO, Paris, pp. 657–692.
Fritz, S., Scholes, R.J., Obersteiner, M., Bouma, J.A., Reyers, B. A conceptual framework for assessment of the benefits of a Global Earth Observation System of Systems. IEEE Systems Journal, in press.
GEOSS, 2004. Draft GEOSS 10-year Implementation Plan' Draft Reference Document 203-1, Ad hoc Group of Earth Observation, Implementation Plan Task Team. GEO Secretariat, Geneva.
Glibert, P.M., Anderson, D.M., Gentien, P., Granéli, E., Sellner, K.G., 2005. The global, complex phenomena of harmful algal blooms. Oceanography 18 (2), 132–141.
Hakvoort, H., 2006. Innovatie en aardobservatie, wat doet RWS ermee?, RWS-AGI advies en beleid. www.geo-informatie.nl/projects/wrsln/2006/Hakvoort_WRSLN_feb06.ppt Available from:(in Dutch).
Hirshleifer, J., Riley, J.G., 1979. The analytics of uncertainty and information- an expository survey. Journal of Economic Literature 17, 1375–1421.
Isik, M., Hudson, D., Coble, K.H., 2005. The value of site-specific information and the environment: technology adoption and pesticide use under uncertainty. Journal of Environmental Management 76, 245–254.
Kaiser, M.J., Pulsipher, A.G., 2004. The potential value of improved ocean observation systems in the Gulf of Mexico. Marine Policy 28, 469–489.
Kalluri, S., Gilruth, P., Bergman, R., 2003. The potential of remote sensing data for decision-makers at the state, local and tribal level: experiences from NASA's Synergy program. Environmental Science & Policy 6, 487–500.
Lybbert, T.J., Barrett, C.B., McPeak, J.G., Luseno, W.K., 2006. Bayesian herders: updating of rainfall beliefs in response to external forecasts. World Development 35 (3), 480–497.
Macauley, M.K., 2006. The value of information: measuring the contribution of space-derived earth science data to resource management. Space Policy 22, 274–282.
McQuatters-Gollop, M., Raitsos, D.E., Edwards, M., Pradhan, Y., Attrill, M.J., 2007. A long term chlorophyll data set reveals regime shift in North Sea phytoplankton biomass unconnected to nutrient trends. Limnology and Oceanography 52 (2), 625–648.
Morgan, M.G., Pitelka, L.F., Shevliakova, E., 2001. Elicitation of expert judgement of climate change impacts on forest ecosystems. Climate Change 49, 279–307.
Pasterkamp, R., Vermaat, J.E., 2004. Evaluatie toepasbaarheid voorlopige kwantitatieve slibnormen voor Nederlandse kustwateren. IVM report E-04/10 (in Dutch).
Peeters, W., Jolly, C., 2004. Evaluation of Future Space Markets. OECD Publication, Paris. SG/AU/SPA 5, OECD.
Peperzak, L., 2003. Pijpenstelen en mosselsterfte. Zoutkrant mei 2003. RWS-RIKZ, Den Haag (in Dutch).
PricewaterhouseCoopers, 2006. Socio economic benefits analysis of GMES, main report, ESA contract number 18868/05 financed by the European Commission, Brussels.
Rabin, M., 1998. Psychology and economics. Journal of Economic Literature 36 (1), 11–46.
Reid, P.C., Lancelot, C., Gieskes, W.W.C., Hagmeier, E., Weichart, G., 1990. Phytoplankton of the North Sea and its dynamics: a review. Journal of Sea Research 26, 295–331.
RIKZ, 2002. Atlas of near-surface total suspended matter concentrations in the Dutch coastal zone of the North Sea, Report no. RIKZ/2002.059, Rijkswaterstaat, Den Haag.
Roberti, J.R., Zeeberg, J.J., 2007. Does satellite observation of chlorophyll-a and suspended sediment complement Rijkswaterstaat monitoring of the North Sea?, Report no. AGI-2007-GPMP-017, Rijkswaterstaat, Den Haag.

Schimmelpfennig, D.E., Norton, G.W., 2003. What is the value of agricultural economics research. American Journal of Agricultural Economics 85 (1), 81–94.

Songhui, L., Hodgkiss, I.J., Yuzao, Q., Huajie, W., 2000. Similar blooms but different results – a mitigation experience. In: Hallegraeff, G.M., Blackburn, S.I., Bolch, C.J., Lewis, R.J. (Eds.), Harmful Algal Blooms 2000. IOC UNESCO, Hobarth, pp. 458–460.

Stumpf, R.P., Tomlinson, M.C., 2005. Remote sensing of harmful algal blooms. In: Miller, R.L., del Castillo, C.E., McKee, B.A. (Eds.), Remote Sensing of Coastal Aquatic Environments. Springer, Dordrecht, The Netherlands, ISBN 1-4020-3099-1, pp. 277–296.

Trigg, S.N., Roy, D.P., 2007. A focus group study of factors that promote and constrain the use of satellite-derived fire products by resource managers in southern Africa. Journal of Environmental Management 82, 95–110.

Varis, O., Kuikka, s., 1999. Learning Bayesian decision analysis by doing: lessons from environmental and natural resources management. Ecological Modelling 119, 177–195.

VermaatJ, Bouwers, L., Turner, K., Salomons, W. (Eds.), 2004. Managing European Coasts- Past, Present and Future. Springer Verlag, Berlin, ISBN 3-540-23454-3.

Williamson, R.A., Hertzfeld, H.R., Cordes, J., Logsdon, J.M., 2002. The socioeconomic benefits of earth science and applications research: reducing the risks and costs of natural disasters in the USA. Space Policy 18, 57–65.

Woerd, H.J. van der, Blauw, A., Pasterkamp, R., Tatman, S., Laanen, M., Peperzak, L., 2005. Integrated spatial and spectral characterisation of harmful algal blooms in Dutch coastal waters (ISCHA)-Demonstration of a HAB service in the Zeeuwse Voordelta. IVM report R 05/09, Amsterdam.

Woerd, H.J. van der, Blauw, A., Peperzak, L., Pasterkamp, R. A harmful algal bloom warning system for the North Sea: a combination of field data, remote sensing and computer models for algal growth and bloom transport, Journal of Sea Research, submitted for publication.

Yokota, F., Thompson, K.M., 2004. Value of information analysis in environmental health risk management decisions: past, present and future. Risk Analysis 24 (3), 635–650.

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How valuable are satellite observations of seawater quality?

Global Earth Observation (GEO), such as satellite observations, helps manage environmental resources and prevent disasters. However, they are expensive. A recent study proposes a framework to assess the value of GEOs in which stakeholders are consulted.

GEO consists of all observational information about the state of the world, including satellite observations and 'in situ' information. Many governments and international organisations invest a large amount in GEO to inform their decisions. However, there have been recent budgetary pressures on GEO. To assess its benefits, the European Commission has funded the GEO-BENE project[1], which supported this Dutch study. The study proposes a framework based on 'Bayesian decision theory', whereby the probability that a decision-maker will invest in information depends on how much uncertainty will be reduced by the information.

In order to assess the framework, the study assessed the value of satellite observations to monitor water quality in the North Sea. More specifically, the study examined three case studies: eutrophication (observed via chlorophyll-a – the pigment (colour) from algae, which acts as an indicator of eutrophication), excessive algal blooms and suspended sediments. A range of stakeholders was consulted, including policy makers, water managers, researchers and representatives of interest groups, using a questionnaire based on Bayesian decision theory.

On average, the results demonstrate that respondents expect satellite observations to improve water quality monitoring in the North Sea. This expectation is greatest for suspended sediments. It is considered slightly less valuable for monitoring for algal blooms and least valuable for eutrophication as respondents believed a well-functioning water monitoring system already exists and there is a good understanding of the relationship between source and effects.

Estimates of economic pay-offs could only be made for an early-warning system for algal blooms, based on an event in 2001 where algal bloom caused an approximate loss of EUR 20 million to the Dutch mussel farming industry. From this, the study estimated a value for satellite observations of EUR 74,000 per week for monitoring algal blooms. Since the total additional costs of satellite observations are about EUR 50,000 per week, the net benefits were estimated at EUR 24,000 per week. This suggests a social rate of return of 48 per cent. It is difficult to estimate economic pay-offs for eutrophication as more than 85 per cent of nutrients which cause eutrophication come from poorly controllable sources, such as historical stocks of phosphates and nitrates and atmospheric deposits. Hence, better information about chlorophyll-a's spread contributes little to better-targeted interventions.

The authors acknowledge much uncertainty surrounding the estimates used in the study, particularly those arising from participants' assumptions about the reliability of GEO information. However, when accounting for these uncertainties, the probability that investments in early warning enhance welfare is still 75 per cent.

The study concludes that Bayesian decision theory provides a suitable framework for assessing the economic value of GEO information through stakeholder consultation, but that it requires a high level of expertise and awareness from the respondents to quantify their responses. It also indicates the importance of including several decision-makers in the consultation since estimates of value vary depending on background, expertise and possible allegiance to existing monitoring systems or organisations.

1. GEO-BENE (**G**lobal **E**arth **O**bservation – **B**enefit **E**stimation: **N**ow, **N**ext and **E**merging) was supported by the European Commission under the Sixth Framework Programme). See www.geo-bene.eu
2. See http://ec.europa.eu/environment/water/marine/index_en.htm

Source: Bouma, J.A., van der Woerd, H.J. and Kuik, O.J. (2009). Assessing the value of information for water quality management in the North Sea. *Journal of Environmental Management.* 90: 1280-1288.
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Theme(s): Environmental Information Services, Marine Ecosystems, Water

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How valuable are satellite observations of seawater quality?

Global Earth Observation (GEO), such as satellite observations, helps manage environmental resources and prevent disasters. However, they are expensive. A recent study proposes a framework to assess the value of GEOs in which stakeholders are consulted.

GEO consists of all observational information about the state of the world, including satellite observations and 'in situ' information. Many governments and international organisations invest a large amount in GEO to inform their decisions. However, there have been recent budgetary pressures on GEO. To assess its benefits, the European Commission has funded the GEO-BENE project[1], which supported this Dutch study. The study proposes a framework based on 'Bayesian decision theory', whereby the probability that a decision-maker will invest in information depends on how much uncertainty will be reduced by the information.

In order to assess the framework, the study assessed the value of satellite observations to monitor water quality in the North Sea. More specifically, the study examined three case studies: eutrophication (observed via chlorophyll-a – the pigment (colour) from algae, which acts as an indicator of eutrophication), excessive algal blooms and suspended sediments. A range of stakeholders was consulted, including policy makers, water managers, researchers and representatives of interest groups, using a questionnaire based on Bayesian decision theory.

On average, the results demonstrate that respondents expect satellite observations to improve water quality monitoring in the North Sea. This expectation is greatest for suspended sediments. It is considered slightly less valuable for monitoring for algal blooms and least valuable for eutrophication as respondents believed a well-functioning water monitoring system already exists and there is a good understanding of the relationship between source and effects.

Estimates of economic pay-offs could only be made for an early-warning system for algal blooms, based on an event in 2001 where algal bloom caused an approximate loss of EUR 20 million to the Dutch mussel farming industry. From this, the study estimated a value for satellite observations of EUR 74,000 per week for monitoring algal blooms. Since the total additional costs of satellite observations are about EUR 50,000 per week, the net benefits were estimated at EUR 24,000 per week. This suggests a social rate of return of 48 per cent. It is difficult to estimate economic pay-offs for eutrophication as more than 85 per cent of nutrients which cause eutrophication come from poorly controllable sources, such as historical stocks of phosphates and nitrates and atmospheric deposits. Hence, better information about chlorophyll-a's spread contributes little to better-targeted interventions.

The authors acknowledge much uncertainty surrounding the estimates used in the study, particularly those arising from participants' assumptions about the reliability of GEO information. However, when accounting for these uncertainties, the probability that investments in early warning enhance welfare is still 75 per cent.

The study concludes that Bayesian decision theory provides a suitable framework for assessing the economic value of GEO information through stakeholder consultation, but that it requires a high level of expertise and awareness from the respondents to quantify their responses. It also indicates the importance of including several decision-makers in the consultation since estimates of value vary depending on background, expertise and possible allegiance to existing monitoring systems or organisations.

1. GEO-BENE (**G**lobal **E**arth **O**bservation – **B**enefit **E**stimation: **N**ow, **N**ext and **E**merging) was supported by the European Commission under the Sixth Framework Programme). See www.geo-bene.eu
2. See http://ec.europa.eu/environment/water/marine/index_en.htm

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DOPLNENIE RADU MESAČNÝCH HODNÔT TEPLOTY VODY DUNAJA V STANICI BRATISLAVA ZA OBDOBIE 1901–1925

Ján Pekár, Pavla Pekárová, Milan Onderka, Pavol Miklánek, Peter Škoda

Cieľom štúdie je odvodenie modelov na nepriamy výpočet priemerných mesačných hodnôt teploty vody v toku. Navrhnuté sú dva typy modelov na simuláciu mesačných teplôt vody Dunaja v stanici Bratislava. Prvý model vychádza z multiregresného vzťahu medzi mesačnými teplotami vody a mesačnými teplotami vzduchu vo Viedni a prietokmi v stanici Bratislava. Druhý typ modelu predstavuje autoregresný Boxov-Jenkinsov model s troma regresormi: teplotou vzduchu, druhou mocninou teploty vzduchu a prietokmi. Modely boli kalibrované na údajoch z obdobia 1950–1980. Multiregresný model bol použitý na doplnenie mesačných hodnôt teploty vody Dunaja v stanici Bratislava pre obdobie 1901–1925. Získali sme tým kontinuálny 100-ročný rad mesačných hodnôt teploty vody v stanici Bratislava.

KĽÚČOVÉ SLOVÁ: mesačné teploty vody, Dunaj v Bratislave, regresné modely, SARIMA modely

SUPPLEMENTATION OF THE MEAN MONTHLY WATER TEMPERATURES IN THE DANUBE AT BRATISLAVA STATION IN PERIOD 1901–1925. The aim of this study is to create models for indirect calculation of instream water temperature. This paper presents two types of models for simulation of monthly water temperatures in the Danube River at the Bratislava gauge station. One model has been created on the basis of a multi-regression relationship between monthly water temperatures and monthly air temperatures (averages) in Vienna, Austria, and river discharge recorded at Bratislava. The other model is based on autoregressive Box-Jenkins approach with three regressors: air temperature, squared air temperature and discharge. The models presented here were calibrated with a data set covering the period 1950–1980. The multi-regression model was successfully used for filling in a gap in the historical records with monthly water temperatures of the Danube River at Bratislava, 1901–1925.

KEY WORDS: monthly water temperature, Danube River, Bratislava, regression models, SARIMA models

Úvod

Nakoľko na Slovensku máme k dispozícii kontinuálne merania teploty vody na Dunaji v stanici Bratislava od roku 1926, zostavili sme modely, pomocou ktorých by sme mohli simulovať vývoj priemerných mesačných hodnôt teploty vody v Dunaji už od roku 1876. Tieto modely simulujú teplotu vody na základe meraných hodnôt teploty vzduchu v stanici Viedeň a priemerných mesačných prietokov Dunaja v Bratislave.
Regresné modely na nepriamy výpočet teploty vody z teploty vzduchu použili napr. Morrill a kol. (2001, 2005), Webb a kol. (2003), Webb a Nobilis (2007). Albek (2007) využil regresnú analýzu na odvodenie viacerých modelov teploty vody z teploty vzduchu a prietoku. Tieto modely môžu byť súčastne použité na simuláciu teploty vody vzhľadom na zvyšovanie teploty vzduchu ako dôsledku globálneho otepľovania. Jednoduché regresné modely používajú ako jeden z parametrov aj prietok vody, ktorý sa môže v dôsledku klimatických zmien zvyšovať alebo znižovať.
Cieľom štúdie je zostavenie multiregresného a autoregresného modelu na simuláciu mesačných hodnôt teploty vody v závislosti na mesačných teplotách vzduchu vo Viedni a mesačných prietokoch v Dunaji v stanici Bratislava.

Použité údaje

Pri odvodení modelov sme použili priemerné mesačné teploty vody Dunaja, počítané z denných hodnôt, meraných o 7,00 hod. ráno vo vodomernej stanici Bratislava (obr. 1). Tento rad sa vo všeobecnosti považuje za rad denných hodnôt teploty vody. Teplota vody v Bratislave sa kontinuálne pozoruje už od roku 1925. Meranie teploty vody bolo do roku 1993 vykonávané 1x denne medzi 7,00-8,00 hod. Nádoba na meranie teploty vody s teplomerom bola ponorená do prúdiacej vody čo najďalej od brehu na ca 2 minúty a teplota bola odčítaná s presnosťou na desatinu °C. Merania teploty vody v Bratislave po krát zhodnotili a výpadky v meraní za niektoré mesiace za obdobie 1926–1950 doplnili Dmitrijevova a Pacl (1952).

Pri hodnotení hydrologického režimu Dunaja sme použili priemerné denné prietoky vyhodnocované vo vodomernej stanici Bratislava za obdobie 1926–2005 (obr. 2). Z výsledkov analýz ročných prietokov vyplýva, že dlhodobý priemer ročných prietokov Dunaja v stanici Bratislava sa nemení, v posledných rokoch sa zmenil ročný chod prietokov – odteká viac vody v zimnom období a menej v letných mesiacoch (Pekárová a kol., 2007a,b; Pekárová a Pekár, 2007).

Pri výbere klimatickej stanice sme analyzovali homogenitu meraní teploty vzduchu z viacerých staníc (napr. Bratislava: letisko – obr. 1, Hurbanovo, Praha: Klementínum, Budapešť, Viedeň). Vzhľadom na to, že Dunaj preteká Viedňou (a vzhľadom na najvyššiu koreláciu medzi teplotou vody a teplotou vzduchu) sme ako najvhodnejšiu stanicu s homogénnych radom pozorovaní vybrali stanicu Viedeň. Merania teploty vzduchu (mesačné priemery) zo stanice Viedeň sú k dispozícii už od roku 1875.

Výsledky

Multiregresný model

Za účelom simulácie priemerných mesačných teplôt vody v stanici Bratislava sme viacnásobnou regresiou odvodili empirické vzťahy pre nepriamy výpočet teploty vody na základe meraných mesačných teplôt vzduchu v stanici Viedeň a prietokov v stanici Bratislava za obdobie 1951–1980. Odvodené vzťahy majú tvar:

$$To=0.5504\ Ta+0.03407\ Ta^2 - 0.001050\ Ta^3 - 0.000307\ Q + 0.988\ sez + 1.23; \qquad Ta > -5°C \qquad (1)$$

$$To=0.155\ Ta + 0.17; \qquad -10°C < Ta < -5°C \qquad (2)$$

kde

To - priemerná mesačná teplota vody v stanici Bratislava [°C];

Ta - priemerná mesačná teplota vzduchu v stanici Viedeň [°C];

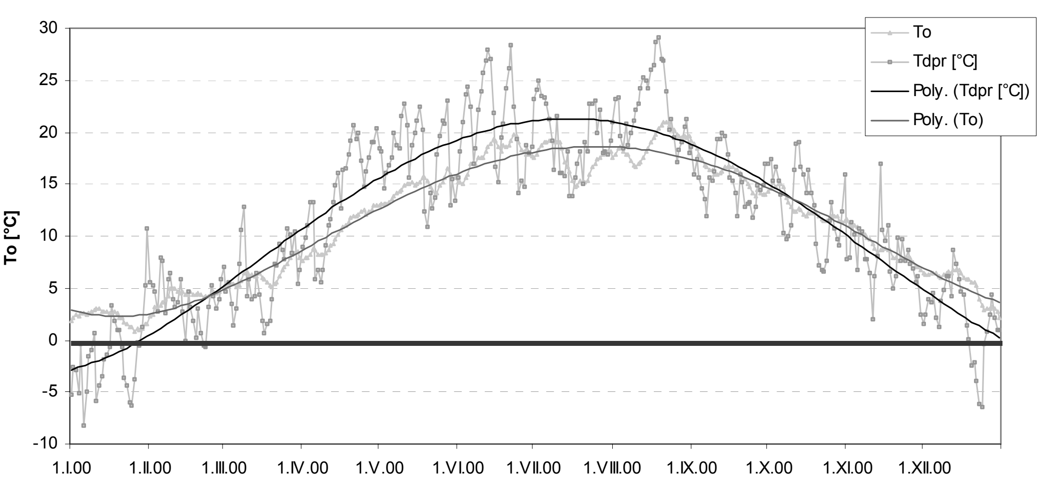
Q - priemerné mesačné prietoky Dunaja v stanici Bratislava [m^3s^{-1}];

sez - parameter vyjadrujúci sezónu (pre mesiace I-VII, *sez*=1, pre VIII-XII, *sez*=2).

Štatistická analýza parametrov modelu je vyhodnotená v tabuľke 1. Štatistická analýza meraných a modelovaných hodnôt potvrdzuje veľmi dobrú zhodu. Porovnanie modelovaných a meraných priemerných teplôt vody za obdobie 1951–1980 je vykreslený na obr. 3a. Verifikácia modelu bola vykonaná na období 1926–1950. Výsledky boli uspokojivé. Preto môžeme vzťahy (1,2) použiť na simuláciu mesačných hodnôt teploty vody.

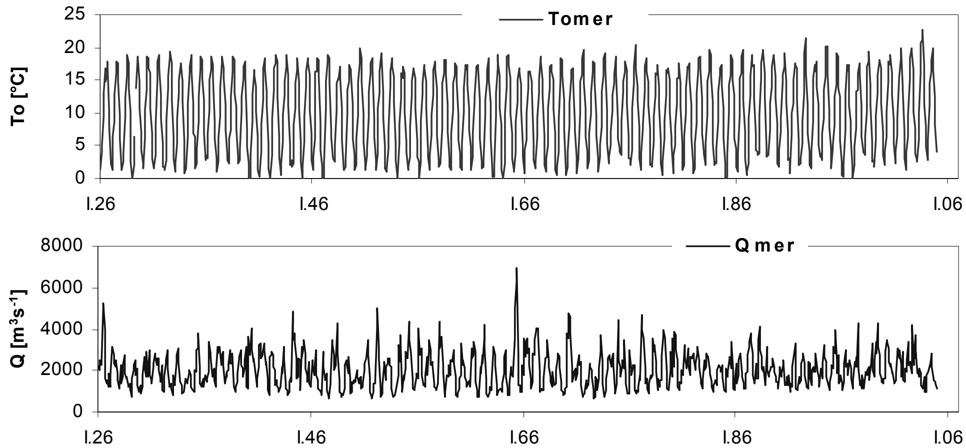
Autoregresný model

Druhý typ modelov, ktoré sme použili predstavujú Box-Jenkinsove autoregresné modely typu ARIMA(p, d, q)x $(P,T,Q)_{12}$. Opis týchto modelov možno nájsť napr. v práci Pekárová (2003). Pri kalibrácii modelov ARIMA sme použili štatistický softwér STATGRAPHICS.



Obr. 1. Príklad priebehu meraných denných hodnôt teploty vody v Dunaji a teploty vzduchu v stanici Bratislava v roku 2000.

Fig. 1. Example of the measured daily Danube water temperatures time course, and of the air temperatures, station Bratislava, year 2000.



Obr. 2. Priebeh priemerných mesačných teplôt vody To a priemerných mesačných prietokov (obdobie 1926–2005) Dunaja v stanici Bratislava. (Značenie I.26 na osi x znamená január 1926, I.06 – január 2006).

Fig. 2. Time course of the mean monthly water temperatures To, and of the mean monthly discharges (O), station Bratislava, period 1926 – 2005. (The time scale begins with January 1926 (I.26) and ends with January 2006).

Tabuľka 1. Štatistiky multiregresného modelu. Závislá premenná: *To*
Table 1. Multiregression model statistics. Dependent variable *To*

Parameter	Odhad	Št. Chyba	t- štatistika	P-hodnota
CONSTANT	1.23003	0.133121	9.23995	0.0000
Ta	0.550419	0.012542	43.8861	0.0000
Ta^2	0.0340682	0.00162823	20.9235	0.0000
Ta^3	-0.00105	0.00006199	-16.9444	0.0000
Sez	0.988377	0.0606983	16.2834	0.0000
Q	-0.000307	0.0000416	-7.38556	0.0000

R-squared = 98.1299 percent — Mean absolute error = 0.641994
R-squared (adjusted for d.f.) = 98.1199 percent — Durbin-Watson statistic = 1.6495
Standard Error of Est. = 0.831946

Tabuľka 2. Štatistiky autoregresného modelu – (výstup zo softvéru STATGRAPHICS)
Table 2. Autoregression model statistics – (software STATGRAPHICS output)

Vybraný model: ARIMA(1,0,0)x(1,0,0)12 s konštantou + 3 regresory, Q, Ta, Ta^2
Počet prvkov: 360
Počet mesiacov pre verifikáciu modelu: 12

Štatistika	Kalibračné Obdobie	Verifikačné Obdobie
MSE	0.430351	0.36940
MAE	0.503876	0.50565
MAPE	60.2856	11.307
ME	-0.000681	0.05399
MPE	41.1238	1.63043

ARIMA Model

Parameter	Odhad	Št. chyba	t štatistika	P-hodnota
AR(1)	0.160182	0.0115974	13.8119	0.000000
SAR(1)	0.0692769	0.0147684	4.69089	0.000004
Q	-0.000248	0.00005327	-4.66105	0.000005
Ta	0.586844	0.0176378	33.2719	0.000000
Ta^2	0.0041806	0.00075152	5.56291	0.000000
Mean	2.39751	0.135847	17.6486	0.000000
Constant	1.87398			

Estimated white noise variance = 0.437759 with 357 degrees of freedom
Estimated white noise standard deviation = 0.661634
Number of iterations: 17

Testované boli viaceré typy modelov. Ako najlepší bol vyhodnotený model ARIMA$(1,0,0)x(1,0,0)_{12}$ s konštantou a troma regresormi: Q, Ta, Ta^2. Parametre modelu sú v tabuľke 2.

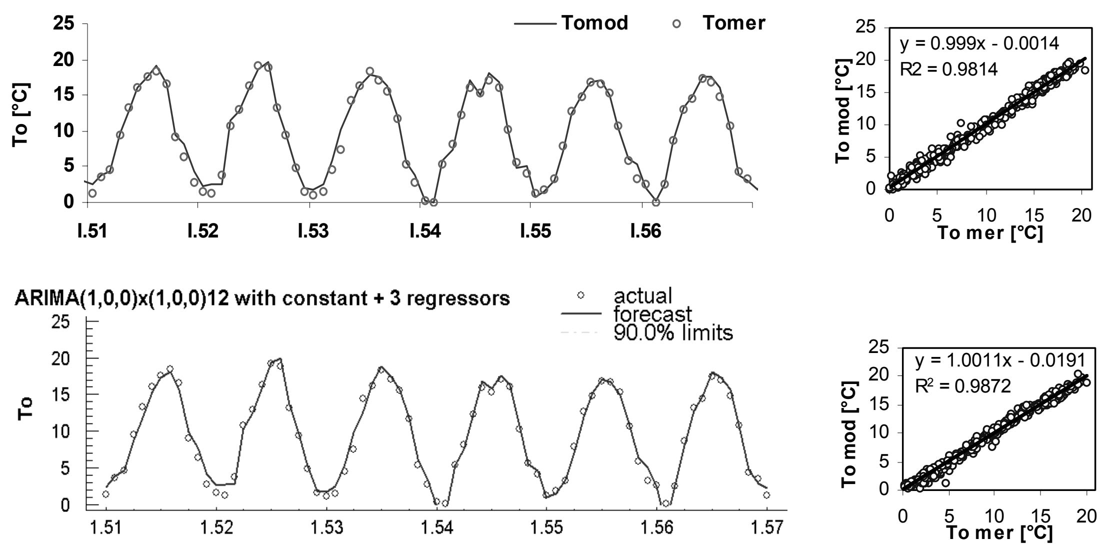
Aj keď autoregresný model vykazuje mierne lepšie štatistické charakteristiky, ako model multiregresný (obr. 3), vzhľadom na jednoduchosť multiregresného modelu (1)-(2) budeme používať tento model. Na vytvorenie multiregresného modelu stačí softvér EXCEL, na spustenie ARIMA modelu je potrebný niektorý štatistický softvér, napr. STATGRAPHICS.

Doplnenie priemerných mesačných teplôt vody Dunaja 1901–1925

Na doplnenie priemerných mesačných teplôt vody v Dunaji v stanici Bratislava za obdobie 1901–1925 sme použili jednoduchý multiregresný model (1)-(2). Doplnené – modelované – mesačné teploty vody sú vykreslené na obr. 4 a ročné priemery modelovaných a meraných teplôt vody sú vykreslené na obr. 5. Doplnené priemerné mesačné teploty vody Dunaja v stanici Bratislava sú uvedené v tabuľke 3.

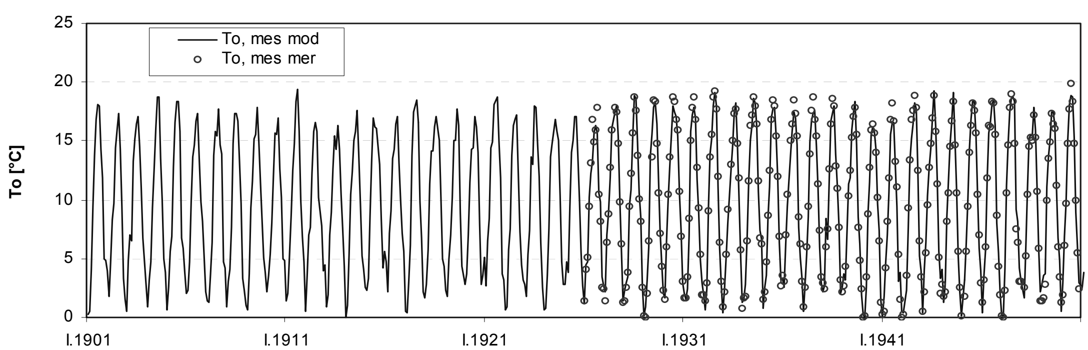
a)

b)



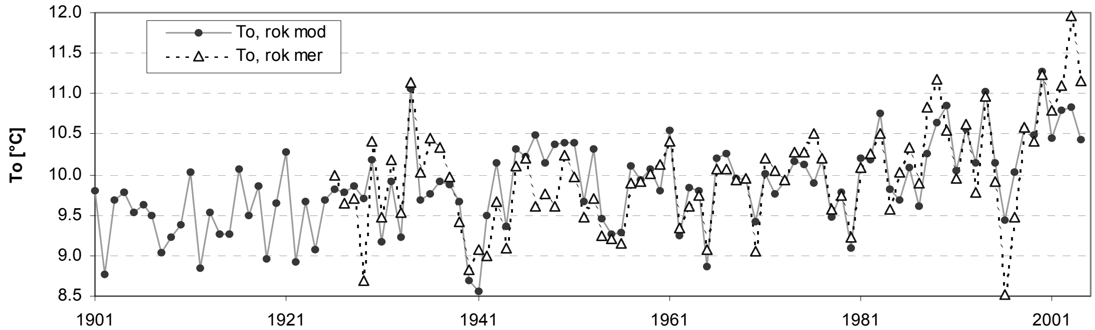
Obr. 3. Priebeh meraných a modelovaných mesačných hodnôt (vľavo) a porovnanie meraných a modelovaných hodnôt (vpravo) teploty vody v Dunaji v stanici Bratislava, obdobie 1951–1980. a) multiregresný model; b) ARIMA model.

Fig. 3. Time course of the measured and modeled monthly values (left), and comparison of the measured and modeled values (right), of the Danube water temperatures at Bratislava within the 1951–1980 period: a) multiregression model, b) ARIMA model.



Obr. 4. Priebeh meraných a modelovaných mesačných hodnôt teploty vody v Dunaji v stanici Bratislava, obdobie 1901–1950.

Fig. 4. Time course of the measured and modeled mean monthly Danube water temperatures at Bratislava station, period 1901–1950.



Obr. 5. Priebeh meraných a modelovaných ročných hodnôt teploty vody v Dunaji v stanici Bratislava, obdobie 1901–2004.
Fig. 5. Time course of the measured and observed mean yearly Danube water temperature values at Bratislava station, period 1901–2004.

Tabuľka 3. Doplnené priemerné mesačné teploty vody Dunaja v stanici Bratislava multiregresným modelom za obdobie 1901–1925
Table 3. The supplemented mean monthly Danube water temperature values at Bratislava station, by a multiregression model, period 1901–1925

rok	1	2	3	4	5	6	7	8	9	10	11	12	To, rok
1901	0.25	0.47	4.07	9.44	13.82	16.81	18.17	18.01	14.24	11.80	5.02	4.79	9.8
1902	3.90	1.81	4.83	8.23	9.73	14.47	15.94	17.31	14.34	9.39	3.27	1.49	8.8
1903	0.51	4.84	7.01	6.55	13.31	15.22	16.45	17.13	14.51	10.95	6.71	2.81	9.7
1904	0.93	3.21	4.70	9.37	12.80	16.02	18.71	18.74	13.51	10.01	4.98	3.83	9.8
1905	0.61	2.60	5.57	6.94	12.71	16.59	18.40	18.31	15.79	6.70	5.85	3.78	9.5
1906	2.01	2.29	4.74	9.76	13.62	14.68	16.66	17.36	13.67	9.87	8.14	2.20	9.6
1907	1.40	1.29	3.70	6.34	13.84	15.82	15.49	17.73	14.73	13.94	4.73	4.19	9.5
1908	0.89	3.07	4.13	7.59	14.85	14.68	17.35	16.76	13.25	9.74	3.30	2.26	9.0
1909	0.99	0.61	3.71	9.36	11.63	15.15	15.56	17.83	14.97	11.46	5.09	3.77	9.2
1910	2.16	3.54	5.34	8.06	12.00	15.74	15.53	16.97	12.64	10.20	5.03	4.91	9.4
1911	1.35	2.09	5.13	8.71	12.55	14.85	18.38	19.38	15.78	10.00	6.90	4.72	10.0
1912	0.47	3.56	7.04	7.67	12.29	15.80	16.62	15.80	10.26	7.74	3.97	4.51	8.8
1913	0.90	1.93	7.01	8.99	12.62	15.45	14.28	16.36	14.24	10.42	7.50	4.29	9.5
1914	0.04	1.01	5.37	10.47	12.31	15.03	15.86	17.54	14.07	9.58	5.18	4.07	9.3
1915	2.52	2.33	3.29	8.72	13.32	16.98	16.22	16.10	13.00	8.41	4.23	5.58	9.3
1916	4.66	2.23	7.12	9.05	13.56	14.25	16.41	17.03	13.20	9.96	7.10	5.55	10.1
1917	0.51	0.34	3.08	6.07	13.82	17.43	18.04	18.51	16.61	9.86	6.75	2.21	9.5
1918	1.72	2.83	5.72	11.33	14.18	14.21	16.22	17.04	15.03	10.15	5.02	4.36	9.9
1919	2.31	1.74	4.96	7.01	10.16	15.00	15.05	17.70	16.27	8.89	4.28	3.56	9.0
1920	2.77	3.72	6.99	11.48	14.23	14.36	17.12	16.23	14.08	7.91	2.86	3.52	9.6
1921	5.04	2.63	6.50	8.37	14.47	14.98	18.10	18.79	14.93	11.87	3.75	3.19	10.3
1922	0.66	0.83	5.79	7.54	13.84	16.35	16.83	17.23	12.49	7.21	4.52	3.19	8.9
1923	2.75	1.76	5.39	7.43	13.59	12.97	17.93	17.81	14.86	12.03	6.35	2.56	9.7
1924	0.65	0.82	3.63	7.58	13.62	16.35	16.85	15.82	15.07	10.38	4.76	2.84	9.1
1925	2.85	4.66	3.85	9.43	14.09	15.06	17.15	17.12	13.65	9.96	5.48	2.62	9.7

Závery

V práci boli odvodené dva modely na nepriamy výpočet mesačnej teploty vody v toku: 1. jednoduchý multiregresný model a 2. ARIMA model. Tieto modely majú široké uplatnenie pri štúdiu rôznych ekologických a environmentálnych problémov. Aj keď autoregresný model vykazuje mierne lepšie štatistické charakteristiky, ako model multiregresný, vzhľadom na jednoduchosť multiregresného modelu (1)-(2) sme v tejto práci použili model multiregresný na predĺženie meraní teploty vody do minulosti od roku 1901 do roku 1930. Je zaujímavé, že modelované ročné teploty vody vo vodnom roku 1996 nadhodnocujú merané teploty a v suchom roku 2003 ich podhodnocujú.

Odvodené modely je ďalej možné použiť napríklad aj pri identifikácii nehomogenity meraní teplotných radov, pri doplnení chýbajúcich meraní, alebo pri simulácii budúceho vývoja teploty vody v tokoch za použitia scenárov prietokov (Szolgay a kol., 2007).

Poďakovanie

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Literatúra:

Albek, M. (2007): Predicting water temperatures based on air temperatures and estimating the effects of climate change, The Third International Conference on Climate and Water, ISBN 978-952-11-2790-8, Finland, 13-18.

Morrill, J. C., Bales, R. C., Conklin, M. H. (2001): The relationship between air temperature and stream temperature. American Geophysical Union, Spring Meeting 2001.

Morrill, J. C., Bales, R. C., Conklin, M. H. (2005): Estimating stream temperature from air temperature: implications for future water quality. J. Envir. Engrg., Volume 131, Issue 1, 139-146.

Pekárová, P., Halmová, D. (2007): Vývoj teploty vody Dunaja v Bratislave za obdobie 1926–2005. Meteorologické zprávy, 60, 6, 183-186.

Pekárová, P., Pacl, J., Škoda, P., Miklánek, P. (2007a): Doplnenie priemerných denných prietokov Dunaja v Bratislave za historické obdobie 1876-1890. Acta Hydr. Slovaca, ISSN 1335-6291, vol. 8, no. 1, 3-12.

Pekárová, P., Halmová, D., Miklánek, P., Pekár, J. (2007b): Analýza zmien maximálnych objemov odtoku Dunaja za dve obdobia 1876–1940 a 1941–2005. Acta Hydrologica Slovaca, ISSN 1335-6291, vol. 8, no. 2, 164-172.

Pekárová, P., Pekár, J. (2007): Viacročná variabilita charakteristík odtoku Dunaja v Bratislave. Acta Hydrologica Slovaca, ISSN 1335-6291, vol. 8, no. 1, 12-21.

Szolgay, J., Hlavčová, K., Lapin, M., Parajka, J., Kohnová, S. (2007): Vplyv zmeny klímy na odtokový režim na Slovensku. Key Publishing, Ostrava, 158 str.

Webb, B., W., Nobilis, F. (2007): Long-term changes in river temperature and the influence of climatic and hydrological factors. Hydrological Sciences–Journal, 52, 1, 74-85.

Webb, B. W., Clack, P. D., Walling, D. E. (2003): Water-air temperature relationships in a Devon river system and the role of flow. Hydrological Processes, 17, 15, 3069-3084.

SUPPLEMENTATION OF THE MEAN MONTHLY WATER TEMPERATURES IN THE DANUBE AT BRATISLAVA STATION IN PERIOD 1901–1925

Aim of this study was a setup of the multiregression and autoregression model, for simulation of monthly values of the water temperatures, in relation upon the monthly mean air temperatures in Vienna, and upon the monthly mean discharges in Bratislava gauging station.

In the first part, based upon a multivariate regression, we derived empirical relationships for the water temperature indirect determination, based upon the measured Vienna air temperatures and discharges at Bratislava, for the 1951- 1980 period.

In the second part, we used the Box-Jenkins autoregression models, type ARIMA (p, d, q) x (P, T, Q)12. Their description can be found in Pekárová (2003). For the ARIMA models calibration, we used the statistical software STATGRAPHICS. Several types of models were tested. As the best one of the evaluated, was the ARIMA(1, 0, 0) x (1, 0, 0)12, with the constant, and with the three regressors Q, Ta, Ta2.

Even if the autoregression model shows a fairly better results as compared to the multiregression one (Fig. 3), with respect to the simplicity of the second model (1)-(2), we will use this second one. For its development, the EXCEL software is sufficient, for ARIMA model implementation, some of the statistical software packages, e.g. STATGRAPHICS, are necessary.

The supplemented (modeled) monthly water temperatures are shown in Fig. 4, and yearly means of the modeled and measured water temperatures are presented in Fig. 5. The supplemented mean monthly Danube water temperatures in Bratislava gauging station are given in Table 3.

The developed and described models can be of use further on, for the non-homogeneity identification of the measured temperature time series. Also for simulation of the future water temperature development in rivers, using scenarios of the discharge and of the air temperature series (Szolgay et al., 2007).

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Analyzing temporal changes in maximum runoff volume series of the Danube River

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Abstract. Several hypotheses claim that more extremes in climatic and hydrologic phenomena are anticipated. In order to verify such hypotheses it is inevitable to examine the past periods by thoroughly analyzing historical data. In the present study, the annual maximum runoff volumes with *t*-day durations were calculated for a 130-year series of mean daily discharge of Danube River at Bratislava gauge (Slovakia). Statistical methods were used to clarify how the maximum runoff volumes of the Danube River changed over two historical periods (1876–1940 and 1941–2005). The conclusion is that the runoff volume regime during floods has not changed significantly during the last 130 years.

1. Introduction

Apart from the flood peak discharge another very important streamflow characteristic of a river is its runoff volume. Some issues in water management and engineering hydrology require that peak discharge ($Qmax$) and the shape of a flood wave or a flood runoff volume ($Vmax$) are known. In applied hydrology, it is often difficult to assign exact values of a flood wave volume to a particular probability of exceedance and hence to its corresponding T-year discharges. Such relationships are very irregular in nature, so a flood wave hydrograph of a given exceedance probability must be a priory known. Knowledge of flood-wave volumes – as an important hydrological characteristic – was apparent during a flood on the Danube at Komarno (Slovakia) in 1965 (Zatkalik, 1970; Hladny et al., 1970). During this flood event, the river dikes broke under the pressure exerted by the long duration of high water stages, but not because of the extremely high water stages themselves.

In assessing the climate change impacts on the river's runoff regime, it is expected that the increase in air temperature has caused an increase in the extreme flows and flood volumes Vt. Since a 130-year series of the mean daily discharge of the Danube at Bratislava gauging station [11, 12, 13, 14, 15] is available, we could calculate the 130-year series of the highest (annually) *2-, 5-, 10-, 15-, 20-, 25-, 30-* and *60-* consecutive days wave volumes. These series were subsequently divided into two 65-year sub-sets and changes in their probability distribution functions were analyzed.

The aims of the study are to:

1. assess the maximum annual runoff volumes Vt,max lasting *2-, 5-, 10-, 15-,20-, 25-, 30-,* and *60-* days, of the Danube River at Bratislava for the period 1876–2005;
2. determine theoretical exceedance probability curves for maximum runoff volume series;
3. analyze the changes in the maximum runoff volumes for periods: 1876–1940 and 1941–2005.

2. Methods

In Czechoslovakia, Bratranek [2] was the first who investigated the issue of runoff volumes. He used direct and indirect methods of peak vs. flood volume assessment.

The direct method was based on compiling runoff volumes higher than a chosen discharge threshold with assistance of the probability of exceedance (related to the *T*-year return period). The *T*-year discharges were then determined by extrapolating probability curves to the domain of low exceedance probability. In the latter method the author used generalized results of empirical relationships among several flood hydrograph characteristics. In order to determine the runoff volume $W_{20,Q1}$ (Equation 1), the author used not only the highest discharge Q reduced to $(Q_{20} - Q_1)$, but also values of the flood wave duration t_{20}, related to the catchment area.

$$W_{20,Q_1} \approx \frac{3600.t_{20}.Q}{2.10^6} \approx \frac{t_{20}.Q}{556} \tag{1}$$

where: $W_{20,Q1}$ – runoff wave volume with the extreme discharge Q_{20} above the selected threshold Q_1 [mil. m^3];

Q – reduced extreme cumulative discharge ($Q_{20} - Q_1$) [m^{3}s^{-1}];

Q_{20} – extreme *20*-year discharge;

Q_1 – extreme *1*-year discharge;

t_{20} – the average flood wave duration of the reduced discharge ($Q_{20} - Q_1$) [hrs].

The main disadvantage of this method is that it is not applicable for flood wave volumes with smaller exceedance probabilities than once in 20 years.

Cermak [3] studied the flood wave volumes of flood events with peaking above the long-term annual mean discharge Q_a on the regional scale. Beard [1] also used theoretical exceedance probability curves and the parameter *t* – for flood wave duration, to determine the annual extreme runoff volumes. The values of *t*- parameter depend on the catchment characteristics of the river being studied [5, 9]. However, the author selected only one value for the extreme runoff volumes in every year of the data sets.

A method described in detail by [10] was used to calculate the maximum runoff volume series for various runoff wave duration *t = 2, 5, 10, 15, 20, 25, 30,* and *60* days.

3. Results

3.1. Assessment of the maximum t-day runoff volume (1876–2005)

In calculations of the annual maximum runoff volumes of particular durations, a reconstructed 130-year series of mean daily discharge (1876–2005) of the Danube at the Bratislava gauging station was used (Figure 1), Pekarova et al. (2007a). The maximum annual *t*-day flood volume was determined for each year. The runoff volume series are shown in Figure 2. Considering the *2*-day and *5*-day maximum runoff volumes, the flood of 1899 was the highest one within the period 1875–2005. But considering the *10*- to *60*-day runoff volumes, the highest flood was that of 1965.

3.2. Theoretical exceedance probability curves of the maximum Danube runoff wave volumes

First, a theoretical probability distribution function was chosen for the given duration of runoff and then the *T-year* extreme runoff volumes were calculated. The theoretical distribution function was chosen.

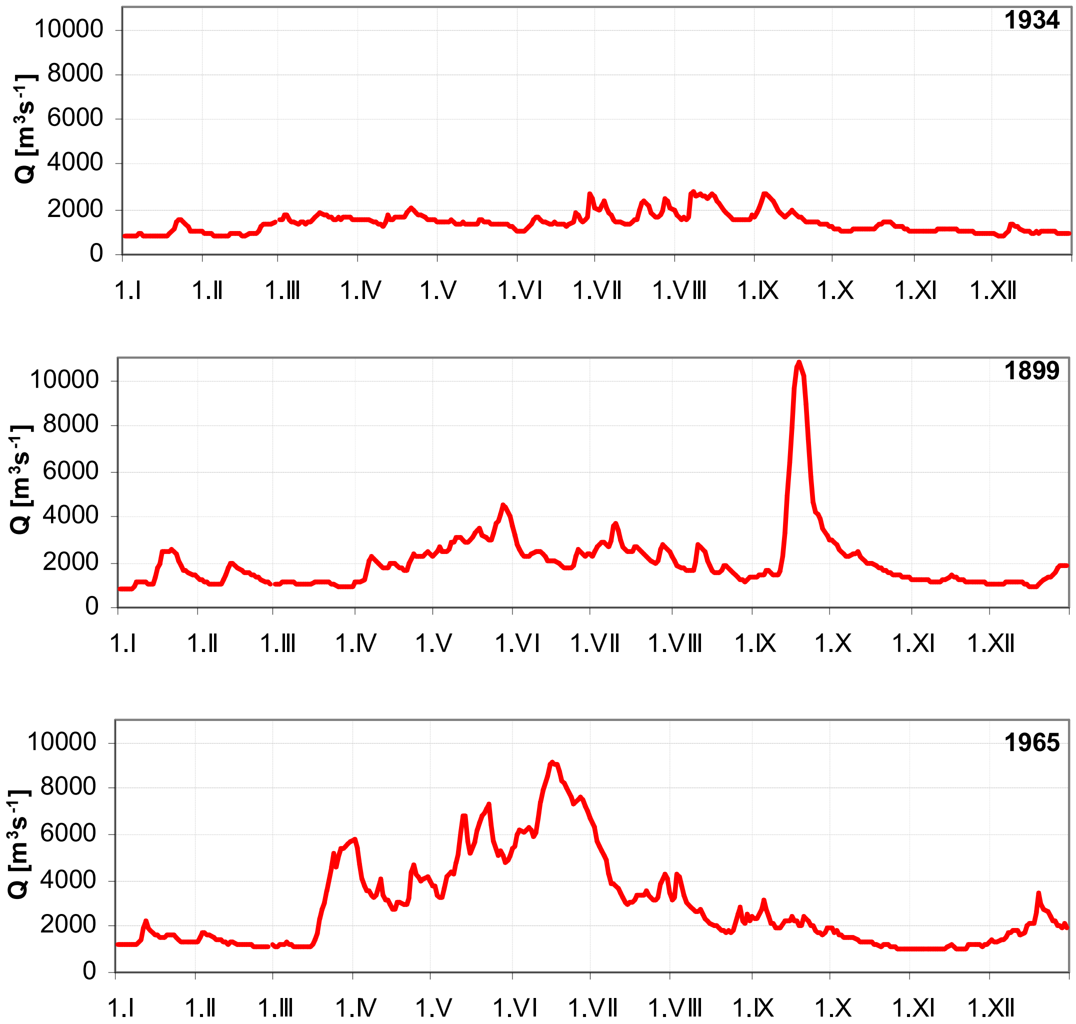


Figure 1. Example of the mean daily discharges (Q).
Year 1934 – the lowest *60*-days runoff volume V_{60};
year 1899 – the highest *2*-days runoff volume V_2; and
year 1965 – the highest *60*-days runoff volume V_{60}.

The relationship between the probability of exceedance p of a certain V_{max} value of the year and the mean return period T is $p = 1/T$. In Slovakia, it is customary that the following formula is used [4, 7, 15]:

$$p = 1 - e^{-1/T}. \tag{2}$$

A log-normal distribution was selected to calculate the *T-year* maximum runoff volume with the given runoff time duration (*t*). The theoretical (log-normal) exceedance probability curves of the runoff volumes with durations *t* equal to *2-, 5-, 10-, 15-, 20-, 25-, 30-*, and *60-* days are demonstrated on a logarithmic-probability scale in Figure 3.

The results suggest (Table 1) that the *100*-year maximum of *2*-day runoff volume (V_2) is 1766 mil m^3, 4079 mil. m^3 for *5*-day (V_5), and 7004 mil. m^3 for *10*-day (V_{10}) runoff volumes.

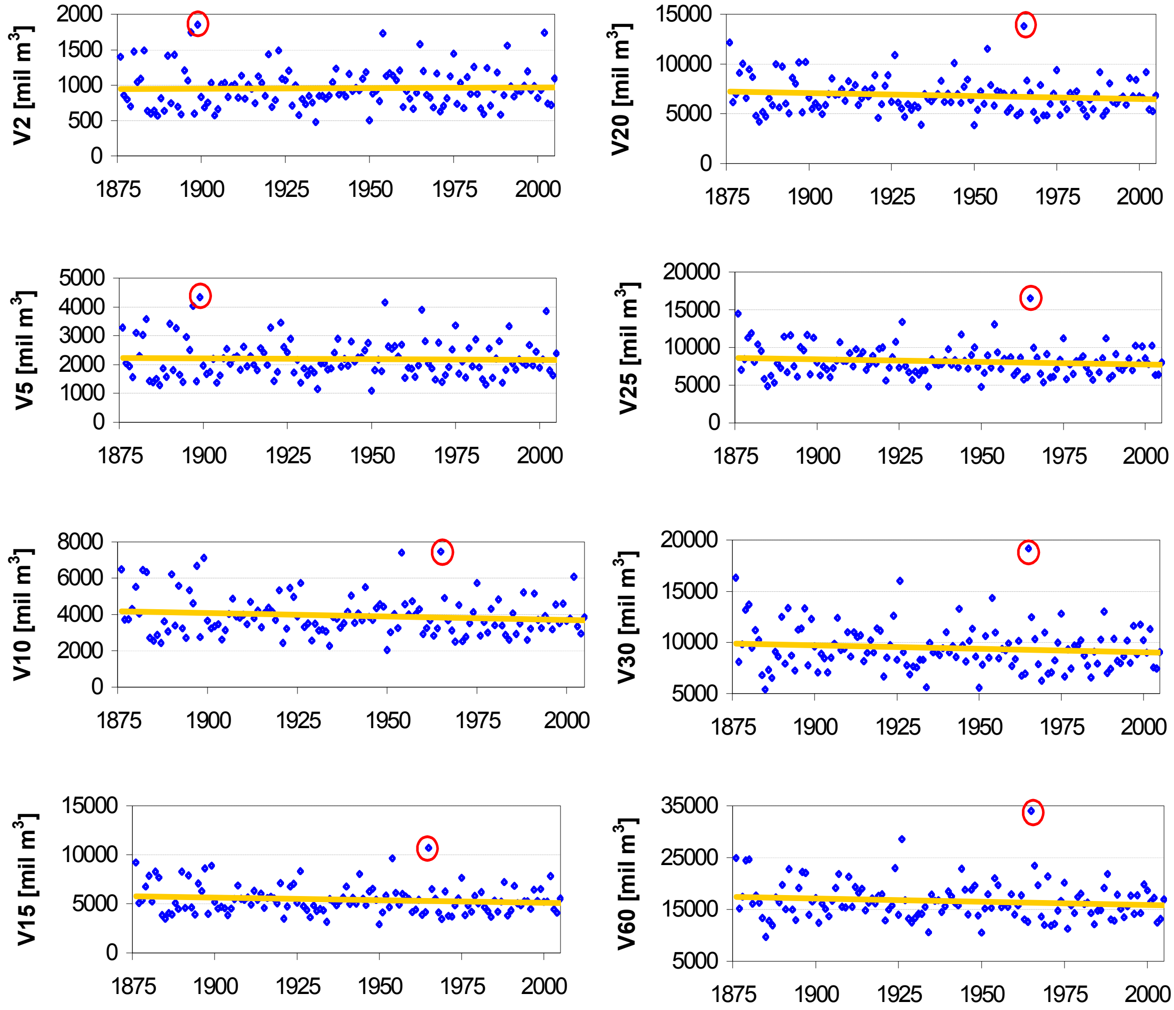


Figure 2. Flood wave volume series of the Danube for various flood durations t (e.g. V_{25} means runoff volume in 25 days).

Table 1. The T-year peak flow $Qmax$ [m^{3}s^{-1}] and the T-year runoff volumes V_t [mil m^3] of the Danube at Bratislava within 1876–2005.

T	1000	500	200	100	50	20	10	5	2	1
P=p.100 %	0.1	0.2	0.5	1	2	4.9	9.5	18	39	63
Qmax	12920	12195	11231	10494	9743	8740	7959	7147	6011	5089
V2	2189	2062	1894	1766	1636	1462	1327	1188	993	836
V5	5070	4773	4379	4079	3775	3370	3055	2730	2278	1915
V10	8566	8100	7480	7004	6519	5868	5359	4829	4084	3477
V15	11281	10706	9936	9343	8735	7916	7271	6596	5638	4848
V20	13874	13189	12271	11562	10834	9849	9073	8256	7093	6130
V25	16172	15402	14368	13567	12742	11625	10741	9807	8473	7362
V30	18350	17504	16364	15479	14567	13328	12345	11305	9811	8563
V60	30658	29352	27586	26209	24782	22833	21276	19618	17217	15187

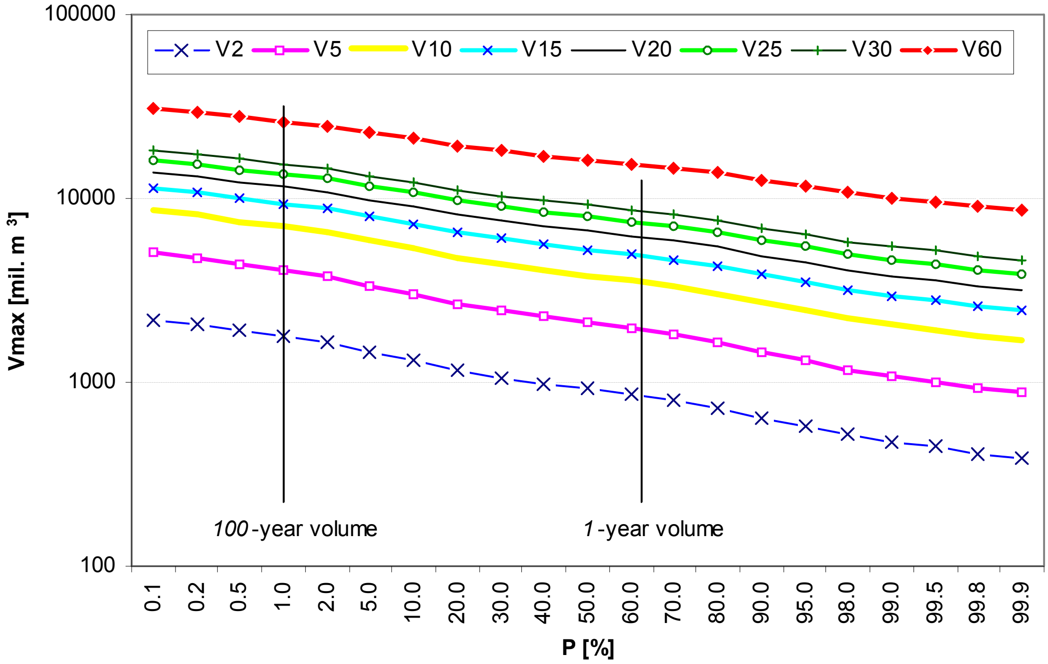


Figure 3. Theoretical (log-normal) frequency curves of the runoff volumes of the Danube at Bratislava, for duration *t* = *2-, 5-, 10-, 15-, 20-, 25-, 30-,* and *60-* days, on logarithmic-probability scale.

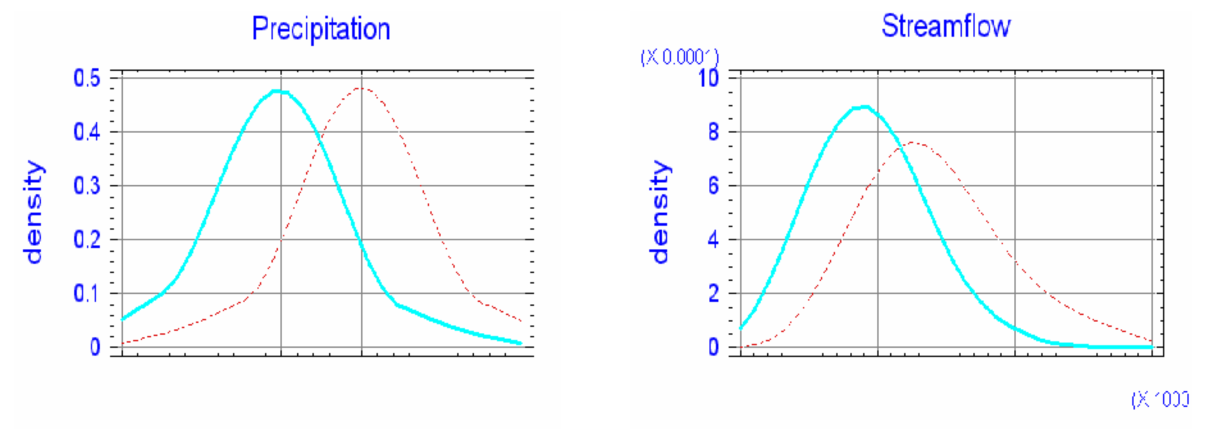
3.3. Maximum runoff volumes analysis for two periods: 1876–1940 and 1941–2005

The IPCC report [6] projects that the increase in air temperature may cause (or already has caused) elevation of extreme streamflows, flood volumes and the number of flood events [8]. A hypothetical example illustrating how the probability density curves of precipitation and runoff series could change is illustrated in Figure 4.

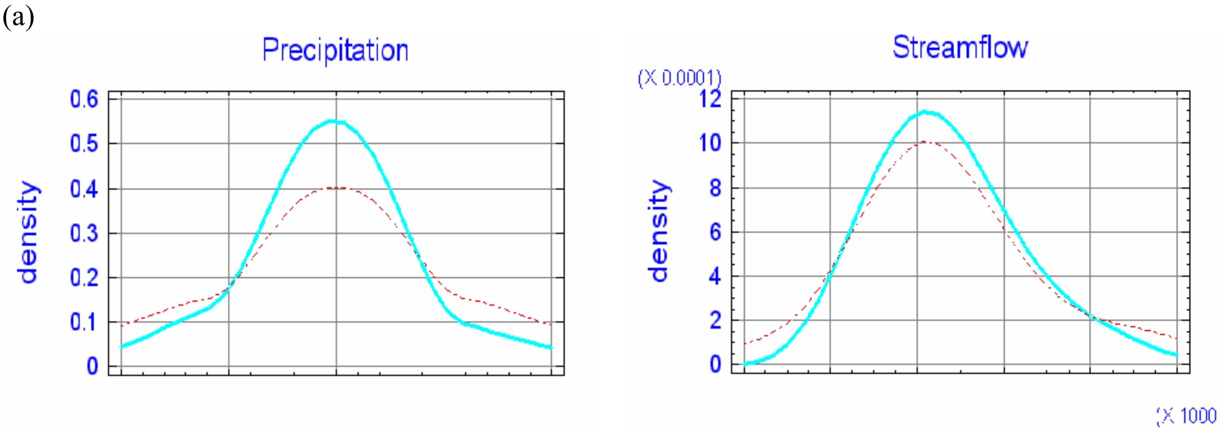
The long-term observations of discharge of the Danube (at Bratislava), and the evaluated series of flood volumes are suitable for testing the severity of the climate change impacts. We divided the original series of 130 years into two sub-sets of 65 years. The basic statistical characteristics of both sub-sets are shown in Table 2.

Table 2. Statistical characteristics of the sub-sets with flood volumes *Vt* [mil m^3] (*Vta* = 1876–1940 and *Vtb* = 1941–2005) for duration *t* = *2-, 5-, 10-, 15-, 20-, 25-, 30-*, and *60-* days.

	V2a	*V2b*	*V5a*	*V5b*	*V10a*	*V10b*	*V15a*	*V15b*
Sum	61201	63014	142199	142866	260081	251060	359266	346474
Aver	942	969	2188	2198	4001	3862	5527	5330
Stdev	**299**	**262**	**702**	**619**	**1166**	**1044**	**1467**	**1383**
Min	477	501	1156	1093	2265	2030	3160	2924
Max	1852	1737	4336	4152	7124	7457	9203	10696
	V20a	*V20b*	*V25a*	*V25b*	*V30a*	*V30b*	*V60a*	*V60b*
Sum	452333	435796	539295	521892	623038	606208	1092510	1067070
Aver	6959	6705	8297	8029	9585	9326	16808	16416
Stdev	**1761**	**1699**	**2030**	**1947**	**2257**	**2205**	**3641**	**3653**
Min	3882	3854	4798	4759	5413	5587	9708	10511
Max	12147	13799	14500	16509	16335	19179	28549	33998



(a)



(b)

Figure 4. Hypothetic change of the density curves of the historical (solid line) and recent periods; a) changes in mean; b) changes in variance.

We tested the hypotheses to find whether the investigated subsets (1876–1940 and 1941–2005) are from the same population. Changes in mean values and in standard deviation were subject to an analysis also. For testing of the hypotheses we used well-known statistical tests t-test (for changes in means) and F-test (for changes in standard deviations).

Test results for means (t-test) are listed in Table 3. The *P*-value is in all cases above 0.05, therefore the null hypothesis stating that both periods have the same mean can not be rejected at the 0.05 confidence level. Also, similar results were found in the case of standard deviations (F-test).

The relevant density curves are demonstrated in Figure 5. Figure 6 illustrates how the probability density curves of the flood volumes changed. It is evident that the curves changed in both directions.

Table 3. Results of the tests of means (variable F and P-value).

	F	*P*-value		F	*P*-value		F	*P*-value
V2	0.319	0.5727	V15	0.619	0.4328	V30	0.437	0.5095
V5	0.008	0.9297	V20	0.702	0.4035	V60	0.374	0.5418
V10	0.511	0.4759	V25	0.589	0.4443	Qmax	0.897	0.3452

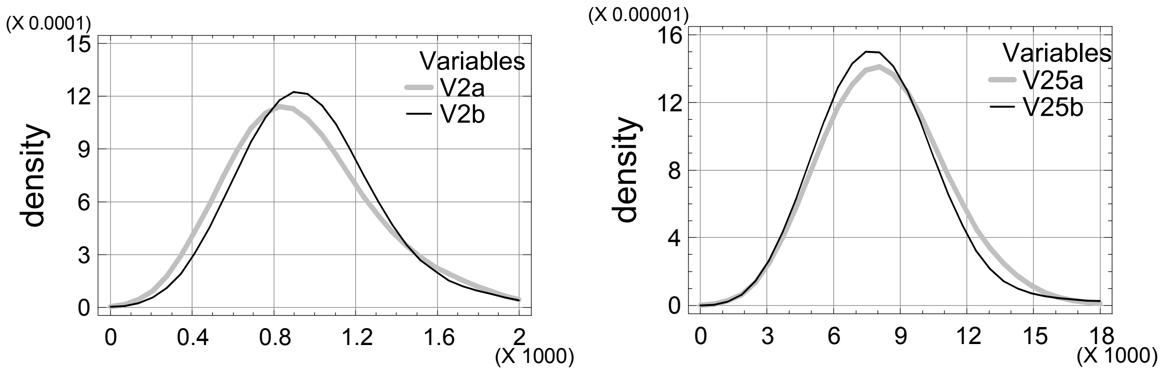


Figure 5. The probability density curves of runoff volume *Vt* for two periods:
V_{ta} – historical period 1876–1940; V_{tb} - recent period 1941–2005; t =2 and 25 days.

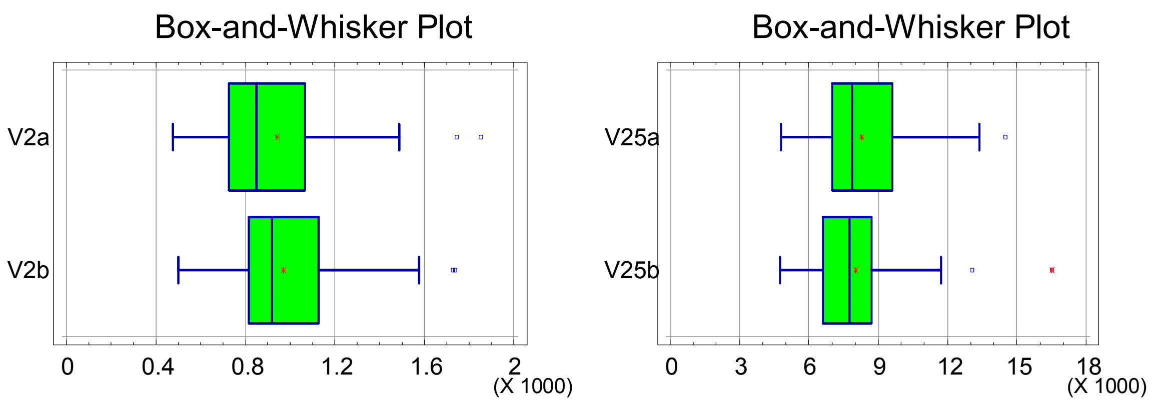


Figure 6. Changes in the statistical characteristics runoff volume *Vt*
of the historical and recent series for flood durations of: a) 2 days, and b) 25 days.

4. Conclusion

Based on the results presented in Table 2 and Table 3 we can conclude that the hypothesis claiming that both series are from the same distribution can not be rejected at the 0.05 significance level. The changes in mean and variance are insignificant (Figure 5 and Figure 6). These results have been confirmed by statistical tests (test of mean equality and test of standard deviation equality) of historical and recent periods for all runoff volume series *V2–V60*).

The conclusion is that the runoff volume regime during floods (in terms of mean values, variances and consequently the probability distribution function) has not changed substantially during the last 130 years, which is of importance to water management. This conclusion pertains not only to the short-term flood runoff episodes (*V2*), but also the long-term ones (*V60*). There is also a possibility to assess the potential flood extent in the case that the flood bank of the Danube River would break again, like in 1965.

With respect to the fact that the Danube River at Bratislava is, to a great extent, a typical Central-European mountainous river with its characteristic flow regime, it is possible to extrapolate these results (particularly those claiming no climate change impact) also to other rivers in Slovakia originating in the region of the Carpathian Mts. In the future, however, it will be desirable to confirm this hypothesis also on other rivers in Slovakia with satisfactory long runoff data series, possibly on the base of reconstructed discharge values by indirect methods (analogy, mathematical runoff modeling etc.).

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References

[1] Beard L R 1956 Statistical Evaluation of Runoff Volume Frequencies Symposium Dorcy IASA Dijon
[2] Bratranek A 1937 Determination of the flood protection storage in reservoirs (in Czech) *Publication No 20* State Hydrological and Hydrotechnical Institute Prague
[3] Cermak M 1956 Flood wave volumes *J. Hydrol. Hydromech.* 4
[4] Dzubak M 1969 Determination of the peak daily precipitation law by means of the global exceedance curves (in Slovak) *J. Hydrol. Hydromech.* **17** 3 pp 209–225
[5] Hladny J Dolezal F Makel M and Sacherova D 1970 Peak runoff volumes of a given duration (in Czech) *Hydrological conditions of the CSSR* Volume III
[6] IPCC 2001 Climate Change 2001 The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the IPCC Cambridge Univ Press UK 944 pp
[7] Kohnova S and Szolgay J 2003 Regional estimation of the index flood and the standard deviation of the summer floods in the Tatry Mountains *J. Hydrol. Hydromech.* **51** 4 pp 241–255
[8] Lapin M and Damborska I 2007 Methods of extreme weather events selection and some results of elaboration Int Conf Bioclimatology and natural hazards Sept 2007
[9] Makel M 1987 Determination of the flood and discharge hydrograph volumes characteristics and their areal variability (in Slovak) Publication 29/I of the SHMU ALFA Bratislava
[10] Mitkova V, Pekarova P and Babiakova G. (2002): Maximum runoff volumes of different duration of the Danube River in dry and wet periods *Acta Hydrologica Slovaca* **3** 2 185–191
[11] Pekarova P, Pacl J, Skoda P and Miklanek P 2007a Supplementation of average daily discharge data of the Danube River in Bratislava with the historical period 1876–1890 *Acta Hydrologica Slovaca* **8** 1 pp 3–12
[12] Pekarova P and Pekar J 2007 Multiannual variability of Danube runoff characteristics in Bratislava gauge *Acta Hydrologica Slovaca* **8** 1 pp 12–21
[13] Pekarova P, Skoda P, Onderka M, Pacl J and Pekar J 2007c Analysis of Discharge Variability of the Danube River in Bratislava for 1876–1940 and 1941–2005 Ed Josip Petraš *10 th International Symposium on Water Management and Hydraulic Engineering* Croatia Zagreb Faculty of Civil Engineering ISBN 978-953-6272-21-1 10 pp
[14] Pekarova P, Miklanek P and Pekar J 2007d Long-term Danube monthly discharge prognosis for the Bratislava station using stochastic models *Meteorological Journal* **10** 4 pp 211–218
[15] Szolgay J Kohnova S Hlavcova K and Minarik M 2007 On the usage of Langbein formula for recurrence period in flood risk assessment (In Slovak) In Cejp Julinek Riha eds. Rizika ve vodnim hospodarstvi *Prace a studie FAST VUT* Brno pp 494–499
[16] Zatkalik G 1970 Calculation of the basic parameters of the discharge hydrographs (in Slovak) PhD Theses p 71

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STATISTICAL EVALUATION OF RUNOFF VOLUME FREQUENCIES OF THE DANUBE IN BRATISLAVA

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Abstract

Evaluation of climate change impacts upon the natural processes is one of the possible methods for verifying hypotheses about the increase of extremes in the observed climatic and hydrologic data series. It relates, of course, to the thorough and detailed analysis of data from the historical observation sets. Trying such evaluations of the statistical characteristics change of the observed data series, we are often confronted with several problems like: short data series, non-homogeneity of the observation series, observation gaps, etc. In the presented study, statistical methods are used for evaluation of changes in the maximum volumes of runoff of the Danube River within two time periods: 1876–1940 and 1941–2005. For calculation of these yearly peak runoff volumes of particular durations, a reconstructed 130-year series of the mean daily discharge of the Danube at Bratislava gauging station was used.

Keywords: *Maximum runoff volume, Danube River, Climate change.*

INTRODUCTION

Apart from a peak runoff the most important flood characteristic is a flood volume. For solution to some water management and hydrotechnical problems it is necessary to know not only values of peak discharge *Qmax* but also a shape of the flood wave or a peak runoff volume *Vmax*. In applied hydrology it is difficult to assign values of flood wave volume to a particular probability of exceedance to corresponding values of *T*-year discharges. Their dependence is irregular to a considerable extent, so it is needed to know a flood wave hydrograph of given exceedance probability, too. The significance of flood wave volume value - as an important hydrological characteristic - was evident during the flood on the Danube in 1965. Then the flood bank broke due to a long duration of higher water levels, not of their extremely high water stage values. Slovak and Czech hydrologists Bratranek, (1937), Cermak, (1956), Dzubak, (1969), Zatkalik, (1970), Hladny et al. (1970) deal with that problems, too.
In assessment of the climate change impacts on the river runoff regime (extremes, flood hydrographs and drought periods), it is expected that the increase of air temperature may cause (or already has caused) the increase of extreme discharges and flood volumes. Considering that we have *130*-year series of the mean daily discharge of the Danube at Bratislava gauging station (Pekarova et al. 2007a-d) at our disposal, we

calculated *130*-year series of the highest yearly *2-, 5-, 10-, 15-, 20-, 25-, 30-* and *60-*daily wave volumes. Those series were subsequently divided into two *65*-year sub-series and changes of their cumulative probability distribution functions were analyzed.
The aims of the study are:
1. to assess the maximum runoff volumes *Vmax* with duration *t* of *2-, 5-, 10-, 15-, 20-, 25-, 30-* and *60*-days, of the Danube river at Bratislava during the period 1876–2005;
2. to depict empirical and determine theoretical probability of exceedance curves for maximum runoff volume series at Bratislava;
3. to analyze the maximum runoff volumes for the Danube river at Bratislava within the two periods: 1876–1940 and 1941–2005.

1. THE MAXIMUM RUNOFF VOLUME ASSESSMENT FOR GIVEN DURATION *t* DAYS FOR THE PERIOD 1876–2005

For calculation of yearly maximum runoff volumes of particular durations, a reconstructed *130*-year mean daily discharge series (1876–2005) of the Danube at Bratislava gauging station was used (Figure 1), Pekarova at al. (2007a).

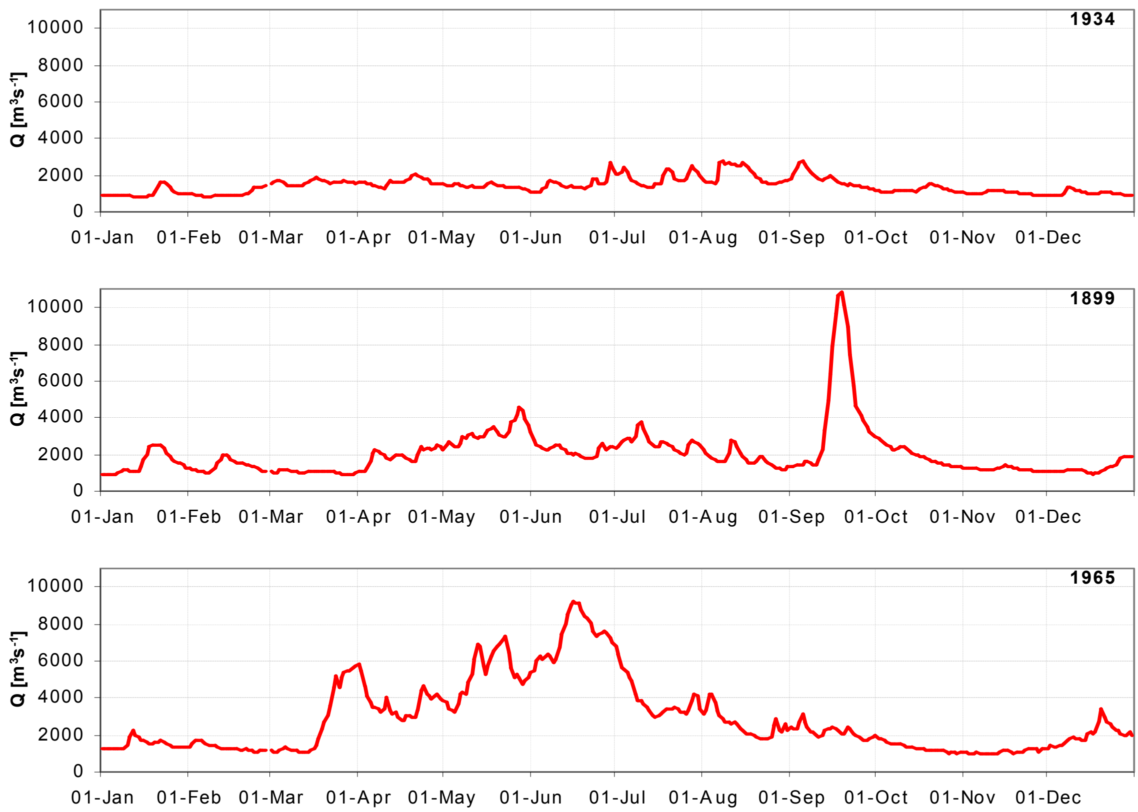


Figure1. Example of the Danube daily mean discharges in several years. Year 1935 – the lowest *60*-daily runoff volume *V60*; year 1899 – the highest *2*-daily runoff volume *V2*; and year 1965 – the highest *60*-daily runoff volume *V60*.

The method described in detail by Mitkova at al. (2002) was used to calculate the maximum runoff volume series for various runoff wave duration *t* (*2, 5, 10, 15, 20, 25, 30* and *60* days). The maximum yearly flood volume was determined for the chosen runoff wave of the *t* duration. The runoff volume series are shown in Figure 2. From the point of view of *2*-day and *5*-day maximum runoff volumes the flood in 1899 was the highest one within the period 1875–2005. If we consider *10*- to *60*-day runoff volumes, then that of the year 1965 was the highest one.

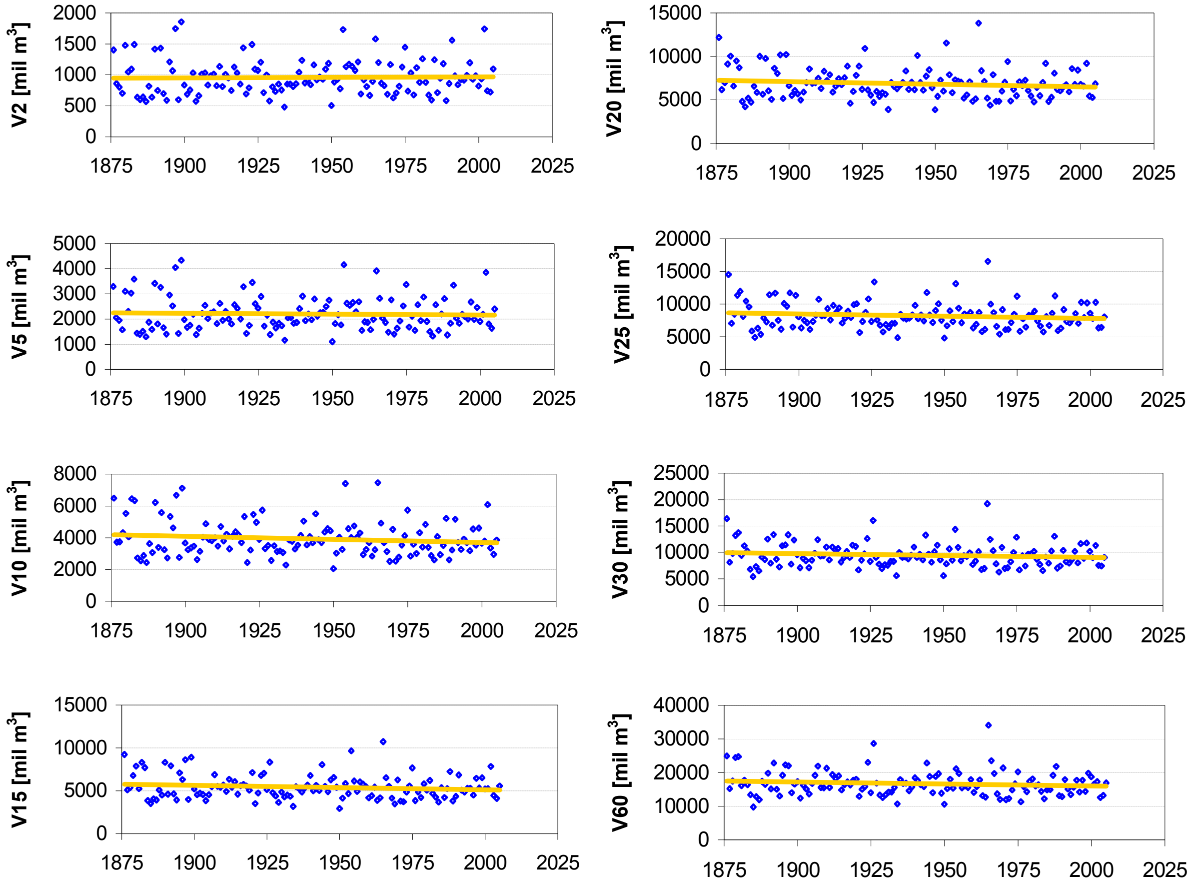


Figure 2. Flood wave volume series of the Danube for various flood durations (e.g. *V15* means runoff volume in 15 days).

2. THE METHODS OF PEAK FLOOD VOLUMES CALCULATION

In Czechoslovakia Bratranek (1937) was the first who was dealing with the problem of the runoff volumes. He used two methods: a direct and an indirect one. In the former one Bratranek compiled runoff volumes higher than the selected discharge thresholds with assistance of the probability of exceedance (related to the *T*-year return period) curves. The *T*-year discharges were determined by extrapolation of these curves to the low exceedance probability domain. In the latter method the author used generalized results of empirical relationships among several flood hydrograph volume characteristics. In order to determine the runoff volume $W_{20,Q1}$ (Equation 1), the author used not only the highest discharge Q reduced to $(Q_{20} - Q_1)$, but also values of the flood wave duration t_{20}, related to the catchment area.

$$W_{20,Q_1} \approx \frac{3600.t_{20}.Q}{2.10^6} \approx \frac{t_{20}.Q}{556} \tag{1}$$

where: $W_{20,Q1}$ – runoff wave volume with the extreme discharge Q_{20} above the selected threshold Q_1 [mil. m^3];

- Q – reduced extreme cumulative discharge $(Q_{20} - Q_1)$ [m^3s^{-1}];
- Q_{20} – extreme *20*-year discharge;
- Q_1 – extreme *1*-year discharge;
- t_{20} – the average flood wave duration of reduced discharge $(Q_{20} - Q_1)$ [hrs].

A disadvantage of this method is, that it is not applicable for flood wave volumes with smaller exceedance probabilities than once in 20 years.
Cermak (1956) studied the flood wave volumes of flood events with the extreme discharge higher than the long-term yearly mean discharge Q_a, in the regional scale. Beard (1956) also used theoretical exceedance probability curves, and also parameter t – flood wave duration, for the determination of the yearly extreme runoff wave volumes. The values of t- parameter depend on the catchment characteristics and on the river size. He selected only one value of the extreme runoff wave volumes in every year for the data sets.

3. THEORETICAL EXCEEDANCE PROBABILITY CURVES OF THE MAXIMUM DANUBE RUNOFF WAVE VOLUMES IN BRATISLAVA

At the first step we chose the theoretical probability density distribution curve for given runoff time duration t and than calculated T-year extreme runoff wave volume values. For the selection of the theoretical exceedance probability curve we used Mitkova et. al. (2002) study, which describes it in detail.
The relationship between the probability of exceedance p of certain V_{max} value of the year and the mean return period T is given as follows:

$$p = 1 - e^{-1/T} . \tag{2}$$

The log-normal distribution was used for calculation of *T-year* maximum runoff volume of the Danube at Bratislava for given runoff time duration t.

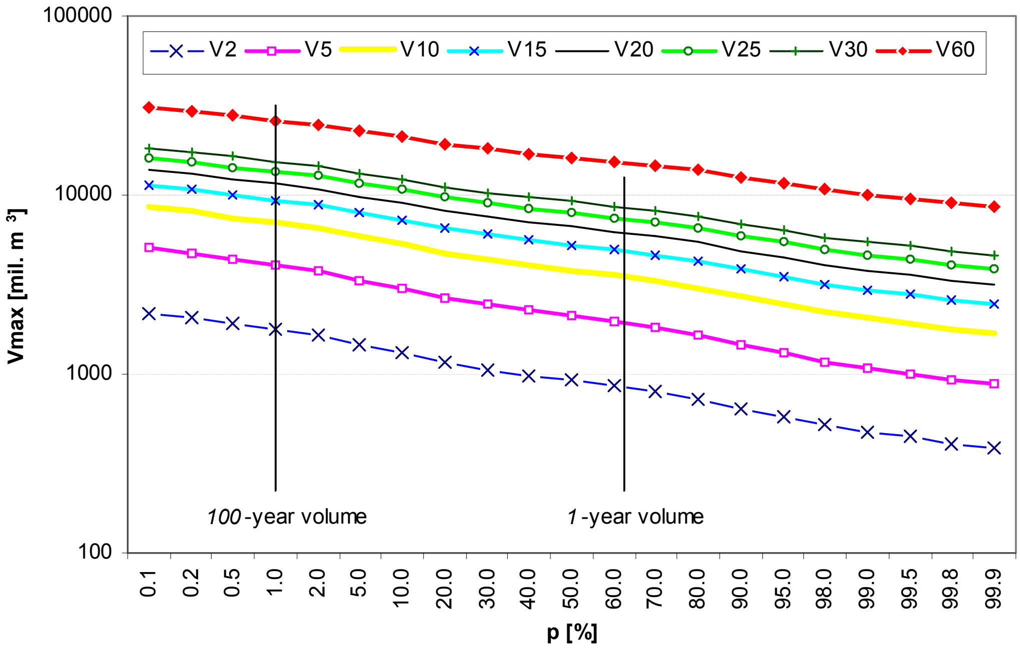


Figure 3. Theoretical cumulative probability density frequencies of the runoff volumes of the Danube at Bratislava, for runoff duration *t* equal to *t* = *2-, 5-, 10-, 15-, 20-, 25-, 30-*, and *60-* days, in logarithmic-probability scale.

Theoretical cumulative probability density frequencies (i.e. the exceedance probabilities) of the runoff volumes of the Danube in Bratislava, for runoff duration *t* = *2-, 5-, 10-, 15-, 20-, 25-, 30-,* and *60-* days, in logarithmic- probability scale are demonstrated in Figure 3.
From the results it follows (Table 1), that *100*-year maximum of *2*-day runoff volume (*V2*) is 1766 mil. m^3, *5*-day (*V5*) one is 4079 mil. m^3 and *10*-day (*V10*) one is 7004 mil. m^3.

Table 1. *T-year* peak flow *Qmax* [m^3s^{-1}] and the *T-year* runoff volumes *Vt* [million m^3] of the Danube at Bratislava within 1876–2005

N	1000	500	200	100	50	20	10	5	2	1
p %	0.1	0.2	0.5	1	2	4.9	9.5	18	39	63
Qmax [m^3s^{-1}]	12920	12195	11231	10494	9743	8740	7959	7147	6011	5089
V2	2189	2062	1894	1766	1636	1462	1327	1188	993	836
V5	5070	4773	4379	4079	3775	3370	3055	2730	2278	1915
V10	8566	8100	7480	7004	6519	5868	5359	4829	4084	3477
V15	11281	10706	9936	9343	8735	7916	7271	6596	5638	4848
V20	13874	13189	12271	11562	10834	9849	9073	8256	7093	6130
V25	16172	15402	14368	13567	12742	11625	10741	9807	8473	7362
V30	18350	17504	16364	15479	14567	13328	12345	11305	9811	8563
V60	30658	29352	27586	26209	24782	22833	21276	19618	17217	15187

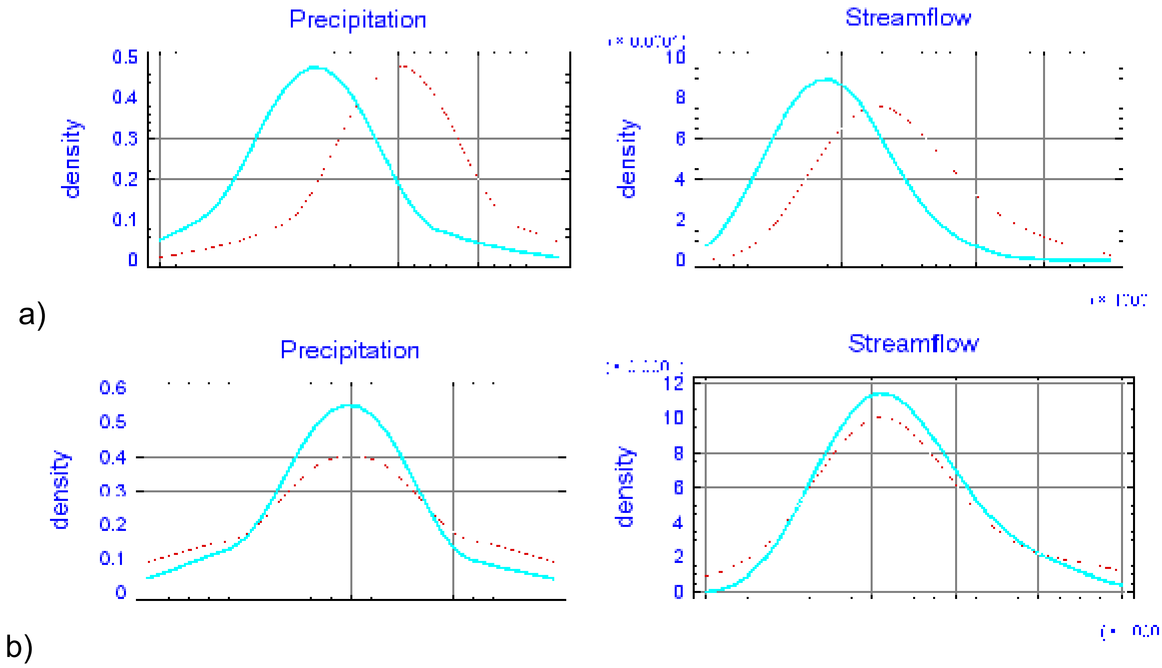


Figure 4. Hypothetic change of the probability density distribution curves of the old (solid line) and new periods; a) changes in mean; b) changes in variance.

4. MAXIMUM RUNOFF VOLUMES ANALYSIS FOR TWO PERIODS: 1876–1940 AND 1941–2005.

From the IPCC report (IPCC, 2001) it follows, that the increase of air temperature may cause (or already has caused) the increase of extreme discharges, flood volumes and also the number of flood events, (Lapin and Damborská, 2007; Pekarova and Pekar, 2007). A hypothetical example, how the probability density distribution curves of precipitation and runoff series could change, is illustrated in Figure 4. The long-term observation series of the Danube discharges at Bratislava, and of the evaluated flood volume series is suitable also for significance tests of the climate change impacts. We divided the original *130*-year series into two sub-series, each of the *65* years of duration. The basic statistical characteristics of both sub-series are given in Table 2.

Table 2. Statistical characteristics of the flood volumes *Vt* [million m^3] time sub-series of the Danube at Bratislava : *Vta* = 1876–1940 and *Vtb* = 1941–2005

	V2a	*V2b*	*V5a*	*V5b*	*V10a*	*V10b*	*V15a*	*V15b*
Sum	61201	63014	142199	142866	260081	251060	359266	346474
Aver	942	969	2188	2198	4001	3862	5527	5330
Stdev	**299**	**262**	**702**	**619**	**1166**	**1044**	**1467**	**1383**
Min	477	501	1156	1093	2265	2030	3160	2924
Max	1852	1737	4336	4152	7124	7457	9203	10696
	V20a	*V20b*	*V25a*	*V25b*	*V30a*	*V30b*	*V60a*	*V60b*
Sum	452333	435796	539295	521892	623038	606208	1092510	1067070
Aver	6959	6705	8297	8029	9585	9326	16808	16416
Stdev	**1761**	**1699**	**2030**	**1947**	**2257**	**2205**	**3641**	**3653**
Min	3882	3854	4798	4759	5413	5587	9708	10511

Max	12147	13799	14500	16509	16335	19179	28549	33998

We tried to test whether the both series (with the differences as shown in Fig. 4.) can be considered statistically belonging to the same population. For the two main statistical parameters of the series, mean and variance, the null hypothesis *H0*: means (variances) are statistically equal against alternative hypothesis *H1*: means (variances) are statistically different were stated. In both cases, the null hypotheses were not rejected on a 0.05 significance level, even for all flood durations. The relevant density distribution curves are demonstrated in Figures 5, some of the tests results are given in Table 3.

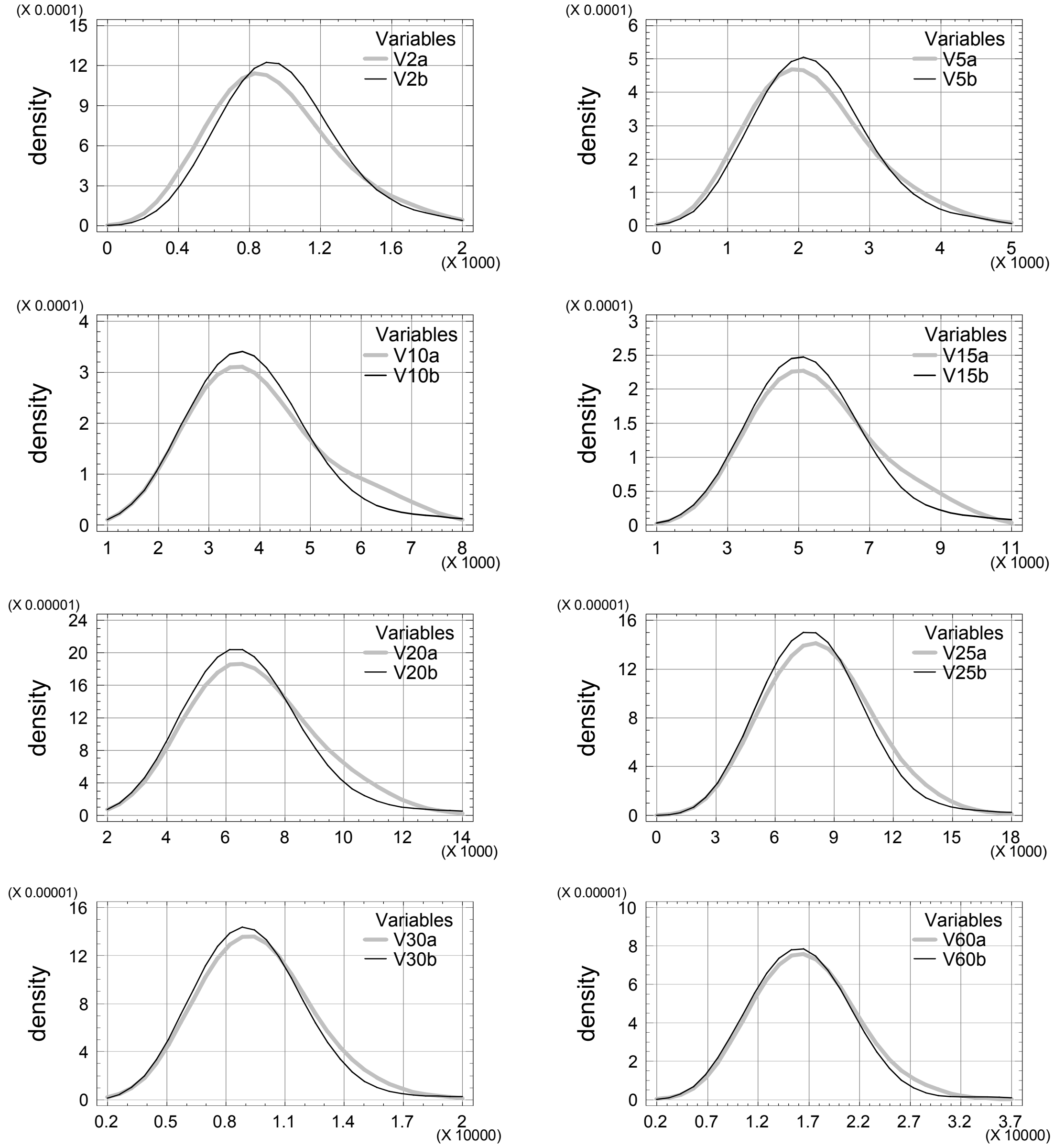
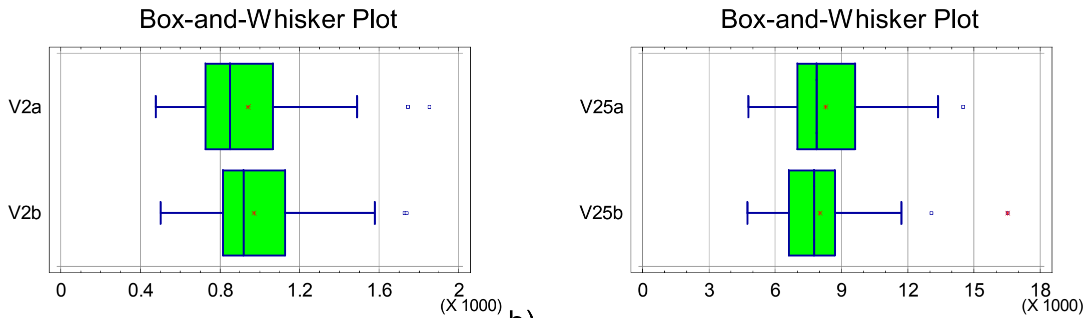


Figure 5. The probability density distribution curves of the different flood volumes of the Danube in Bratislava, for two periods: *Vta* - old period 1876–1940; *Vtb* - new period 1941–2005; *t* – runoff duration.

Table 3. Results of the tests (variable *F* and *P*-value)

	F	P-value		F	P-value		F	P-value
V2	0.319	0.5727	V15	0.619	0.4328	V30	0.437	0.5095
V5	0.008	0.9297	V20	0.702	0.4035	V60	0.374	0.5418
V10	0.511	0.4759	V25	0.589	0.4443	Qmax	0.897	0.3452

In Figure 6 it is illustrated how the probability density distribution curves of the flood volumes of the Danube at Bratislava changed. It can be seen that curves changed in both directions.



a) b)

Figure 6. Change of the statistical characteristics of the old and new series for flood durations: a) *2* days, and b) *25* days.

CONCLUSION

From the results (Table 2 and Table 3) it follows, that the hypothesis of both series belonging to the same distribution was not rejected at the 0,05 significance level, and the changes in mean and variance are neither driven to one direction nor significant (Figure 5 and Figure 6). These results are confirmed by values of the test *H0* (test of mean equality of all old and new runoff volume series *V2–V60*).

The conclusion is that the runoff volume regime during the floods (in term of mean values, variances and consequently of cumulative probability distribution function) has not changed substantially during the last 130 years, which is of importance to water management and water managers. This conclusion pertains not only the short-term flood runoff episodes (*V2*), but also the long-term ones (*V60)*. There is a possibility to assess the potential flood extent in the case when the flood bank of the Danube River would broke, like in 1965.

With respect to the fact that hydrological regime of the Danube River at Bratislava has to a great extent a character of the Central-European mountain river, it is possible to extrapolate these results (particularly those claiming no climate change impact) also for other rivers in Slovakia originating in its Carpathian mountain region. In future, however, it will be desirable to confirm this hypothesis on other Slovak river(s) with long runoff data series, possibly on the base of reconstructed discharge values by indirect methods (analogy, mathematical runoff modeling etc.).

Acknowledgement

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References

Beard, L. R. (1956): Statistical Evaluation of Runoff Volume Frequencies. Symposium Dorcy, IASA, Dijon.
Bratranek, A. (1937): Determination of the flood protection storage in reservoirs (in Czech). Publication No.20, State hydrological and hydrotechnical institute, Prague .
Cermak, M. (1956): Flood wave volumes. Journal of hydrology and hydromechanics, 4.
Dzubak, M. (1969): Determination of the peak daily precipitation law by mmeans of the global exceedance curves (in Slovak). Journal of hydrology and hydromechanics, 17(3), 209-225.
Hladny, J., Dolezal, F., Makel, M., Sacherova, D. (1970): Peak runoff volumes of a given duration (in Czech). Hydrologigal conditions of the CSSR, Volume III.
IPCC (2001): Climate Change 2001: The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the IPCC. Cambridge Univ. Press, UK 2001, 944 pp.
Kohnova, S., Lapin, M., Szolgay, J., Gaal, L. (2005): Methodology for the selection of 10-day maximum precipitation totals and their statistical analysis in the upper Hron region. Contributions to Geophysics and Geodesy, Vol.35/3, 299-318.
Lapin, M., Damborska I. (2007): Methods of extreme weather events selection and some results of elaboration. Int. Conf.: Bioclimatology and natural hazards. Sept. 2007.
Makel, M. (1987): Determination of the flood and discharge hydrograph volumes characteristics, and their areal variability (in Slovak). Publication 29/I of the SHMU, ALFA, Bratislava.
Mitkova, V., Pekarova, P., Babiakova, G. (2002): Maximum runoff volumes of different duration of the Danube River in dry and wet periods. Acta Hydrologica Slovaca, ISSN 1335-6291, vol. 3, no 2, 185–191.
Pekarova, P., Pacl, J., Skoda, P., Miklanek, P. (2007a): Supplementation of average daily discharge data of the Danube River in Bratislava with the historical period 1876–1890. Acta Hydrologica Slovaca, ISSN 1335-6291, vol. 8, no. 1, 3–12.
Pekarova, P., Pekar, J. (2007): Multiannual variability of Danube runoff characteristics in Bratislava gauge. Acta Hydrologica Slovaca, ISSN 1335-6291, vol. 8, no. 1, 12–21.
Pekarova, P., Pekar, J., Onderka, M., Miklanek, P. (2007b): Long-term Monthly Discharge Prognosis for the Danube River in Bratislava. Ed. Josip Petraš, 10 th International Symposium on Water Management and Hydraulic Engineering, 04-09.09.2007 Šibenik, Croatia, Zagreb, Faculty of Civil Engineering, 2007, ISBN 978-953-6272-21-1, 7 pp.
Pekarova, P., Skoda, P., Onderka, M., Pacl, J., Pekar, J. (2007c): Analysis of Discharge Variability of the Danube River in Bratislava for 1876–1940 and 1941–2005. Ed. Josip Petraš, 10 th International Symposium on Water Management and Hydraulic Engineering, 04-09.09.2007 Šibenik, Croatia, Zagreb, Faculty of Civil Engineering, 2007, ISBN 978-953-6272-21-1, 10 pp.
Pekarova, P., Miklanek, P., Pekar, J. (2007d): Long-term Danube monthly discharge prognosis for the Bratislava station using stochastic models. Meteorologický časopis, ISSN 1335-339X, 10, 211–218.
Zatkalik, G. (1970): Calculation of the basic parameters of the discharge hydrographs (in Slovak). PhD Theses, 71 pp.

III.10 SBA WEATHER by GEO-BENE Consortium Partners

Valuing Weather Observation Systems For Forest Fire Management

Nikolay Khabarov, Elena Moltchanova, and Michael Obersteiner

Abstract—**Weather information is an integral part of modern fire management systems. In this paper, we investigate, by means of simulation studies, how improvements in the weather observation systems help to reduce burned area by targeting and monitoring places ripe fires are likely to occur. In our model, the air patrolling schedule is determined by the Nesterov index, which is calculated from observed weather data. We use two weather data sets based on "rough" and "fine" grids. The reduction of the total burned area, associated with an air patrolling schedule based on the "fine" grid, indicates the benefits of using better weather observations. We, also, consider a stochastic model to simulate forest fires and explore the sensitivity of the model with respect to the quality of input data. Finally, we investigate the system of systems effect. We find the largest marginal improvement from the rough grid results when we increase the quality of observations in most critical areas.**

Index Terms—**Fires, forestry, meteorology, value of information, value of observations.**

I. Introduction

EARTH observation has been an integral part of managing human societies for millennia. In the 21st century, mankind has substantially altered the major bio-geochemical cycles on global scales possibly augmenting risks emanating from changes in the behavior of the total Earth system. One of these new risks is linked to an increase in fire calamities, which possibly could cause negative feedbacks to the global carbon cycle, impair ecosystems functions, cause human casualties, and destroy valuable human assets. Thus, in order to attain sustainable development goals, the management of many observation subsystems in a coherent, efficient, and effective manner is needed. For this purpose, a comprehensive Global Earth Observation System of Systems (SoS) should be implemented.

The pathway of benefit generation for fire management, augmented by an Earth observation SoS, is achieved through better informed and, therefore, improved decision making processes resulting in overall reduced net losses. It is the matching of enhanced data streams with a joint knowledge base of fire management that finally results in fewer burned areas. There are many ways fire management can benefit from a global SoS.

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The first benefit that is created, which is, however, the least quantifiable one, is that over the next decades Global and Regional Earth Observation Systems will help revolutionize our understanding of the metabolisms and interrelations of Earth systems leading to fire calamities. In modern societies, knowledge is built in data-intensive evolutionary processes in an agent—information—artifact frame. Hence, at the heart of every good fire management practice lies an entire history consisting of proper data and sophisticated algorithms creating/coding/archiving useful information. Data per se does not have a value—only through its use can the value be generated. Time series of global fire occurrences, causes of ignition and associated fire management responses are currently non-existent. Today, mankind is not in the position to address risks emanating from forest fires on a global scale. Promises and political aspirations to build systems making the globe safer and better equipped to manage global fire risks lack both adequate knowledge and data. In many parts of the world, fire management is inefficient due to the lack of resources and basic knowledge on how to effectively use existing data and data products in all phases of a fire disaster cycle.

The second benefit of a global SoS is generated by *economies of scale*. The societal value of new global data streams increases (linearly or exponentially through network externalities) along with the number of people using it. This consideration is based on the idea of economies of scale and is motivated by the fact that global fire observing systems complementing national systems would lead to overall lower costs for individual countries.

The third benefit arises from *economies of scope*. An individual sub-system of a SoS might serve multiple purposes. In the case of fire management, remotely sensed images are used to detect fires and, at the same time, these images can help generate dynamic land cover maps. Likewise, weather information needed to delineate fire hazard zones garner many other purposes in sectors ranging from agriculture to tourism. Thus, sub-systems and, also, an SoS, have to be understood as information generators operating in a multifaceted production mode.

The fourth benefit we would like to investigate in greater detail in this paper relates to improvements in *efficiency and effectiveness*. The marginal reduction of burned forest area illuminates the benefits of finer resolved weather information used by application of forest patrolling rules to a specific geography.

Section II sets the stage by introducing a simple fire hazard model, relevant data, forest patrolling rules and probabilities' assessment composing together the forest fire fighting model. Then, we articulate the methodology to assess in a quantitative manner the benefits of improved weather observations. Further, in Section III, we focus on the sensitivity of the model with respect to the grid resolution, variation of the number of ground weather stations, and discuss the question of the optimal observation system design. Section IV concludes the paper.

II. Methods and Data

A. *Model and Input Data Description*

The purpose of the model described in the following is to demonstrate how fire management can benefit from the improvements to in-situ measurements and optimizing grid spacing in the application of Earth observations. The effective use of air patrols for forest fire detection is at the model's core. As an example of the air patrolling rules, we utilize the rules developed in the Russian Federation, which are based on the Nesterov index. Some other forest fire danger assessment systems are presented in, e.g., [1] and [2].

Nesterov index is used to assess fire danger on daily basis, and it is the basic indicator for decision making as to implementing particular measures to reduce possible losses due to forest fires. We calculate Nesterov index on two grids: 1) the original "fine" grid and 2) the "rough" grid with the resolution decreased by factor 2 (the number of cells reduced by 2 times on the same area). Further these two grids are referred to as "fine" and "rough" grids. We pick up "small" cell to represent weather data in bigger "aggregated" cell.

We apply official aircraft forest patrolling rules based on Nesterov index, which are in force in Russian Federation and calculate under otherwise equal conditions the losses in terms of the burned forest area and the total patrolled area for both fine and rough grids. After specifying the technical characteristics of an aircraft the total patrolled area can be easily converted into tons of fuel consumed for air patrol. The total cost of the burned area can be calculated taking into account the type of trees growing in the area, the distance from the roads/railways, the amount of CO_2 emissions caused by the fires, etc. The difference between total losses associated with fine and rough grids indicates the benefits of better observations, i.e., using a fine grid for weather observations.

For the calculations we chose the area covering parts of Spain and Portugal located approximately between -7.5 W, 42.0 N and -0.5 W, 38.0 N. The grid cell size is 50×50 km, see Fig. 1. We have chosen this area only because of the availability of weather data. We consider a quite sketchy model with the sole purpose to present the approach of assessment of the value of information for fighting forest fires. Using the same approach the model constants and the set of forest fire patrolling rules can be adjusted to reflect real situation and practices in a particular region.

We use a gridded weather dataset for the year 2000 containing daily temperature, precipitation, and vapor pressure (European Commission—Joint Research Center (JRC) interpolated meteorological data source, JRC/AGRIFISH Data Base: http://mars.jrc.it/marsstat/datadistribution/). The formula for calculating Nesterov index according to [3] is

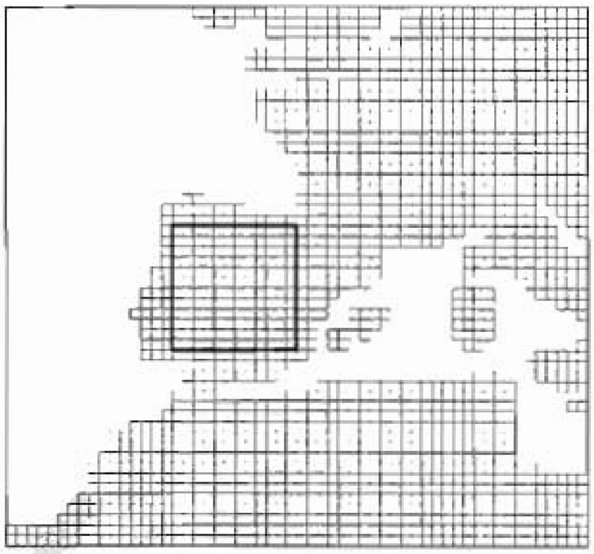

Fig. 1. Study area covering parts of Spain and Portugal.

$$
\begin{aligned}
&I(t) = \sum_{k\in[T_0(t),t]} \left(t_k - t_k^d\right)\cdot t_k \\
&T_0(t) : p(k) < 3 \quad \forall k \geq T_0(t) \quad p\left(T_0(t)-1\right) \geq 3 \\
&I\left(T_0(t)-1\right) = 0 \\
&I(0) = 0 \qquad (1)
\end{aligned}
$$

here t denotes day number since the start of observations (discrete time) for which the Nesterov index is calculated, t_k is the daily temperature in Celsius degrees, t_k^d is the dew point temperature in Celsius degrees for the day k, and $p(k)$ is a daily precipitation in millimeters. The left point of the summing interval $T_0(t)$ is defined such that the interval contains all days with the precipitation less than 3 mm after a day with precipitation of more or equal to 3 mm. The Nesterov index was originally introduced in [4]. The description and applications of Nesterov index, as well as comparison with other similar indices can also be found in [5] and [6]. Fig. 2 shows an example of how Nesterov index depends on time for the cell (4,3) of the area under consideration.

B. *Data Preprocessing*

In order to convert the vapor pressure, which is provided by the weather data set into the dew point temperature required for Nesterov index calculation we use the conversion formulas as follows.

The calculation of saturated water vapor pressure $P(t)$ in hPa $= 100$ Pa depending on temperature t in Celsius we use the Goff-Gratch equation as per [7]

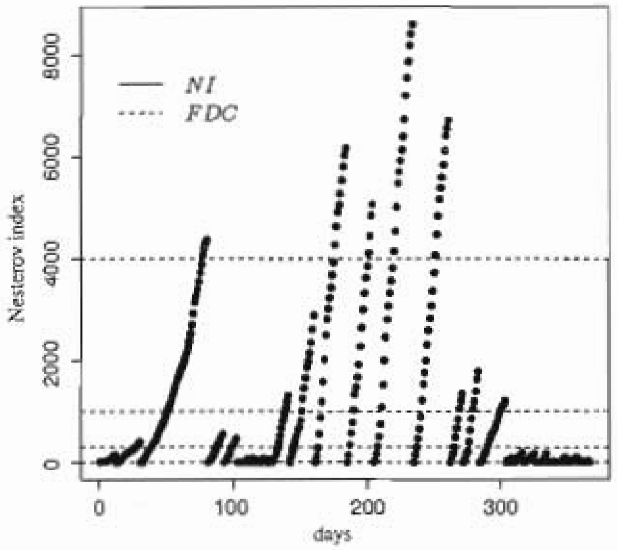

Fig. 2. Daily values of Nesterov index (NI) during the year 2000 for the cell (4,3) and thresholds (FDC) corresponding to fire danger classes.

$$
\begin{aligned}
\bar{t} &= t + 273.15 \\
c_0 &= 373.15 \\
c_1 &= 1013.25 \\
\bar{p}(t) &= -7.90298 \cdot (c_0/\bar{t} - 1) + 5.02808 \cdot \log_{10}(c_0/\bar{t}) \\
&\quad - 1.3816 \cdot 10^{-7} \left(10^{(11.344 \cdot (1-\bar{t}/c_0))} - 1\right) \\
&\quad + 8.1328 \cdot 10^{-3} \left(10^{(-3.49149 \cdot (c_0/\bar{t}-1))} - 1\right) \\
&\quad + \log_{10}(c_1) \\
P(t) &= 10^{\bar{p}(t)}.
\end{aligned}
$$

The calculation of the dew point temperature $\bar{t}^d(t,h)$ based on temperature t in Celsius and relative humidity h is performed according to the following formula:

$$
\begin{aligned}
a &= 17.27 \\
b &= 237.7 \\
\gamma(t) &= a \cdot t/(b+t) + \ln(h) \\
\bar{t}^d(t,h) &= b \cdot \gamma(t)/\left(a - \gamma(t)\right).
\end{aligned}
$$

This formula is based on Magnus-Tetens formula for the vapor pressure according to [8]. The final calculation of the dew point temperature $t^d(t,p)$ based on temperature t in Celsius and vapor pressure p (hPa) is done through

$$t^d(t,p) = \bar{t}^d(t,h), \quad h = p/P(t).$$

C. Forest Fires Patrolling Rules

According to the actual value of Nesterov index in a specific area the fire danger class is determined and corresponding air patrol frequency is applied to that area. Table I is officially used in Russia for that purpose (see [9]). In the following, we show which implications the previously mentioned forest fires strategy coupled with weather data may have on the consequences of forest fires.

TABLE I
FIRE DANGER CLASSES AND AIR PATROL FREQUENCY DEPENDING ON NESTEROV INDEX

Nesterov index	Fire danger	Fire danger class	Frequency of the air patrol
0 ... 300	—	I	No patrol
301 ... 1000	Low	II	Once in 2–3 days
1001 ... 4000	Medium	III	Once daily
4001 ... 10000	High	IV	Twice a day
more than 10000	Extreme	V	Three times a day

D. Probabilities Assessment

We use the formula proposed by Venevsky et al. [10] to assess the probability of the fire occurrence in a forest provided that there is an ignition in the area

$$\bar{P}(I) = 1 - e^{-\alpha I} \quad (2)$$

where I is the Nesterov index, and the value of the parameter α is set to 0.000337. The average number of ignitions during a day according to [10] is expressed in the form

$$N(P_D) = (\kappa(P_D)P_D a + l)\, S \quad (3)$$

where P_D is the population density, $a = 0.1$ is the average number of ignitions in a day produced by one human scaled to one million hectares, l is the probability of fire in some area caused by natural reasons (e.g., lighting), S is the total area of the grid cell in million of hectares, the coefficient κ describes the human ignition potential with respect to population density according to [11]

$$\kappa(P_D) = 6.8 P_D^{-0.57}. \quad (4)$$

The probability of at least one fire in the area given certain population density P_D and Nesterov I index can be expressed in the form

$$P(I, P_D) = 1 - \left(1 - \bar{P}(I)\right)^{N(P_D)} \quad (5)$$

where probability $\bar{P}(I)$ and number of ignitions $N(P_D)$ are calculated using the formulas (2)–(4), respectively.

E. Simplifying Assumptions and Constants

The following is the list of assumptions we made to simplify the assessment of possible forest fires consequences.

1) The whole area under consideration is covered with a homogeneous forest (the fire conditions in a cell are fully determined by weather conditions).
2) The whole area is populated with constant density (the ignition potential is uniformly distributed in the area).
3) There are no extreme winds in the area (we do not account for wind conditions in the model).

In order to be able to calculate the actual outcome of the application of the forest fire fighting policy under certain amount

TABLE II
FIRE DETECTION TIME, BURNED AREA, AND DAILY PATROLLED AREA DEPENDING ON FIRE DANGER CLASS (S_0 IS THE AREA OF A GRID CELL)

Fire danger class, ν	Frequency of air patrol	Fire detection time, $\Delta t(\nu)$, h	Burned area, $d(\nu)$, km^2	Area patrolled daily, $c(\nu)$
I	no patrol	24	0.85	0
II	once in 2 days	12	0.36	$S_0/2$
III	once daily	6	0.08	S_0
IV	twice a day	3	0.03	$2S_0$
V	three times a day	2	0.02	$3S_0$

TABLE III
BURNED AND PATROLLED AREAS FOR ROUGH AND FINE GRIDS AND IMPROVEMENT RATIOS

	Rough grid	Fine grid	Improvement
Burned area, S_b, ha	74 899	55 887	25.38%
Patrolled area, S_p, km^2	112 305 000	108 237 500	3.62%

of information, we need to set several constants discussed as follows.

For the calculations, we set the fire spread rate v equal to 0.3 m/min, which is approximately equal to 0.02 km/h. Under assumption of constant fire spread rate the total area S burned during the time Δt is calculated as the area of the circle of radius $v \cdot \Delta t$.

$$S(\Delta t) = \pi(v \cdot \Delta t)^2.$$

For the sake of simplicity, we assume the fire duration times to be constants depending solely on the fire danger class. We also pose the maximum limit of 24 h for undetected forest fire assuming that satellite observation system will make it possible to detect the fire within this time frame. In addition, we allow 2 h to extinguish the fire and take this time into account to calculate the burned area in Table II. Here, for the sake of simplicity, we do not consider any limitations that might exist with respect to fire fighting resources. One of the possible approaches to dynamic resource allocation is presented in [12].

F. Benefits Calculation Methodology

In the suggested simplified model the only stochastic variable is the occurrence of fire. The probability of fire occurrence depends solely on Nesterov index. This rather rough assumption allows us to assess the value of better weather observations in a quite straightforward way.

Based on the fire detection times and daily patrolled areas both depending on the fire danger class ν as per Table II the calculation of total expected burned S_b and patrolled S_p areas for a 12×12 cell set for one year (365 days) can be performed as follows:

$$\begin{aligned} S_p &= \sum_{t=1}^{365} \sum_{i,j=1}^{12} c\left(\nu_{ij}^t\right) \\ S_b &= \sum_{t=1}^{365} \sum_{i,j=1}^{12} p\left(I_{ij}^t\right) \cdot d\left(\nu_{ij}^t\right) \\ p(I) &= P(I, P_D) \end{aligned} \tag{6}$$

where the fire probability $P(I, P_D)$ is defined in (5). The difference in values of burned area S_b and patrolled area S_p calculated for "rough" and "fine" grids is due to different values of fire danger classes ν_{ij}^t calculated for each cell (i, j) on a daily basis t using "rough" and "fine" weather data, respectively. As we mentioned before, the costs associated with the areas S_b and S_p may be expressed in monetary units.

III. RESULTS

In order to simulate the usage of coarse weather information, a cell from a fine grid should be selected to represent weather information for each cell of a rough grid. There are several options to choose a "small" cell within an "aggregated" cell. Just for illustration purposes, we choose the bottom right cell. Table III summarizes the results. Here, we observe the decrease of both total patrolled area and burned forest.

A. Simulation Approach

In order to investigate the model dynamics in more detail, we have conducted a simulation study, in which we have simulated 1000 fire histories conditional on the weather history observed for the year 2000 for the fine and rough grids, respectively. In each case, the patrolling regime was set up based on the Nesterov index observed by the corresponding grid of weather stations and according to the rules stated in Table I. The fire probability was in both cases evaluated based on the fine-grid Nesterov index, and the daily number of fires was then randomly sampled from a Poisson distribution. The starting times of those fires for each day were sampled uniformly between 06.00 and 18.00, i.e., assuming that no ignition is possible during night. The fire, then, burned either until the arrival of the patrol and was subsequently extinguished, or during the maximum allowed time for detection (24 h) plus extinguishing time.

Two quantities of particular interest were evaluated: the yearly total burned area and the yearly total patrols number. The burned area was estimated under the assumption that the fire spread is circular with a rate of 0.02 km/h. The simulation results for the whole area are summarized in Table IV. The difference between the two models with respect to the estimation of burned area as shown in Tables III and IV is due to the following features of the simulation-based model: 1) it allows for two or more fires during one day in the same area; 2) it calculates the estimation of the burned area in a more accurate way consistent with the inequality $\mathbb{E}(\xi^2) \neq (\mathbb{E}\xi)^2$, which

TABLE IV
SUMMARY OF SIMULATION RESULTS (AVERAGE VALUES)

	Rough grid	Fine grid	Improvement
Burned area, ha	107 417	85 248	20.64%
Number of patrols	45 404	43 772	3.62%
Total fire duration, h	64 650	49 405	23.58%

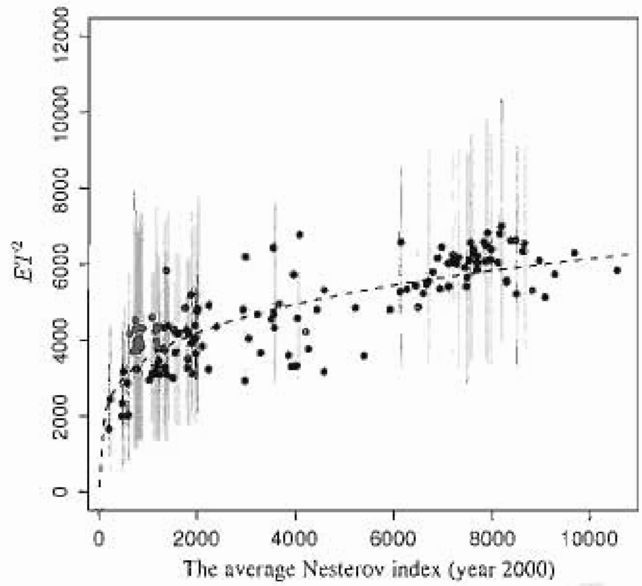

Fig. 3. Dependence of average quadratic fire duration on the average yearly Nesterov index, the gray lines demarcate the 95% confidence intervals, the gray points are the respective means.

holds for any nontrivial random variable ξ; 3) it simulates (random) fire detection time based on the patrolling schedule. The simulation-based model additionally allows us to analyze the burned area distribution.

There is a correlation between the yearly total burned area and the average Nesterov index (see Fig. 3). The change from the fine to the rough grid generally caused both the total duration and the total squared duration distributions to move to the right within each grid cell. The corresponding median dynamics is illustrated in Figs. 4 and 5. Not all individual cells necessarily benefit from the improved information quality. However, as the Table IV shows, on average an improved information system will result in a slightly decreased number of patrols (3.6%) and major savings in terms of burned area (21%).

An example of a positive distribution shift in an individual cell is illustrated on Fig. 6. Not only the average fires become bigger, but the probability of extreme events increases. The latter is true for the whole area, as shown in Fig. 7, where the probability of an event larger than the T^2 is plotted.

B. Sensitivity Analysis

We have considered so far two grid resolutions—"rough" and "fine". The question about the sensitivity of the model to the amount of data used to feed it is of great practical interest. In this section, we use three different methods to adjust the amount of information containing in the input data set: 1) we implicitly vary the number of weather stations and their locations by varying the grid resolution; 2) we explicitly vary the number of

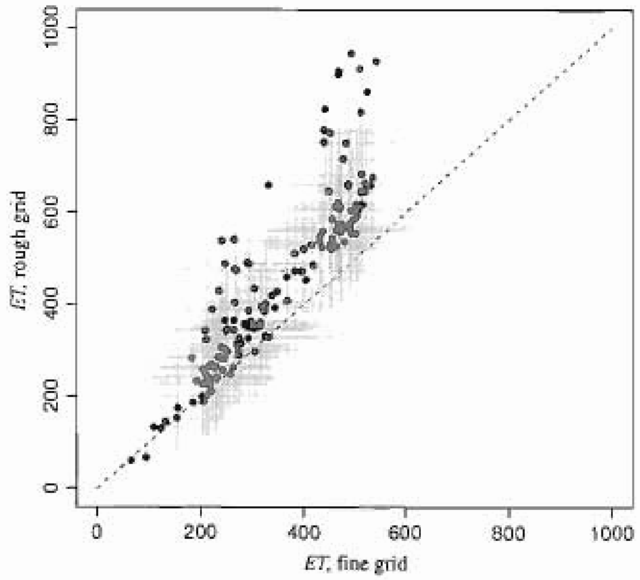

Fig. 4. Expected total yearly fire duration for the patrol regimes defined by fine and rough observation grids. The gray lines demarcate the 95% confidence intervals, the gray points are the respective means. The dotted 45-degree line indicates where the equality would be obtained.

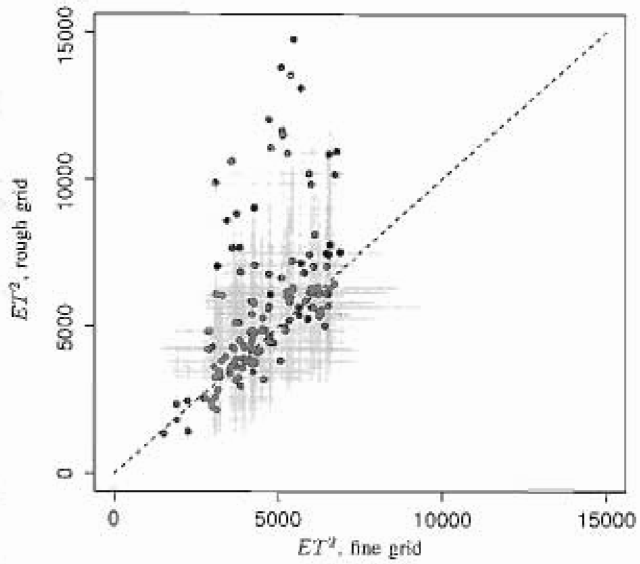

Fig. 5. Expected total yearly quadratic fire duration for the patrol regimes defined by fine and rough observation grids.

weather stations; and 3) we refine the "low" resolution data set in most critical sub-areas.

1) Grid Resolution: In this section, we consider a "smooth" change of a grid cell size and apply the corresponding range of grids to the forest fires fighting model. The purpose of this exercise is to explore how the outcome of the model depends on the grid resolution.

Fig. 8 illustrates several grids with decreasing cell size over the basic grid. The circles show weather stations, which are used to observe weather conditions in specific "big" cells. The rule to select a station to represent weather data within a "big" cell is based on the intersection area of "small" cells with the "big"

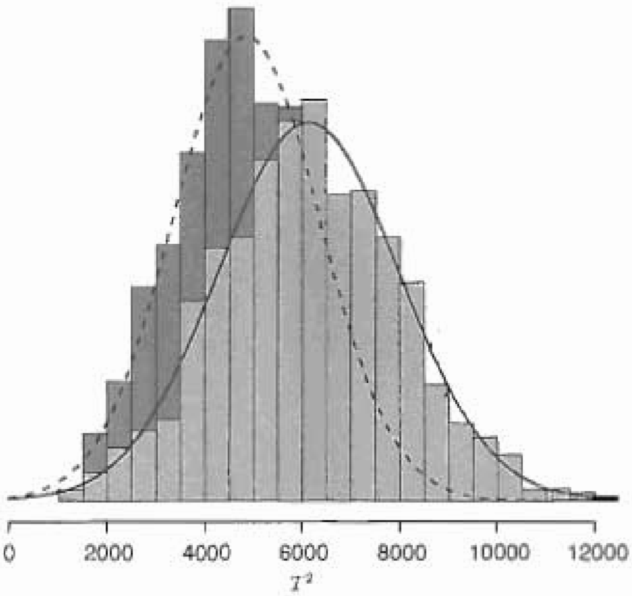

Fig. 6. Simulated distribution of the squared fire duration (T^2) for the fine (dark gray) and rough (light gray) grids. The solid and dotted curves illustrate the corresponding fitted 0-truncated normal densities.

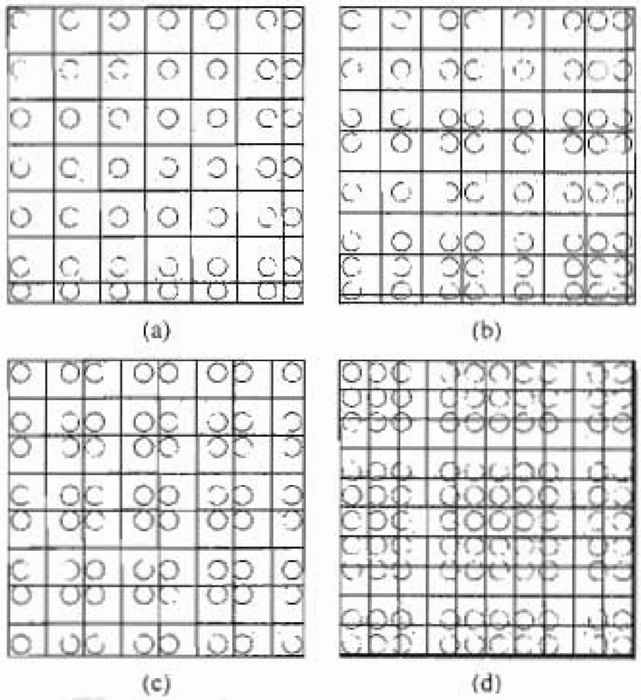

Fig. 8. Grids with decreasing cell size and increasing number of stations over the basic grid. Grid cell sizes are, respectively, (a) 185%, (b) 165%, (c) 150%, and (d) 120% of the original cell.

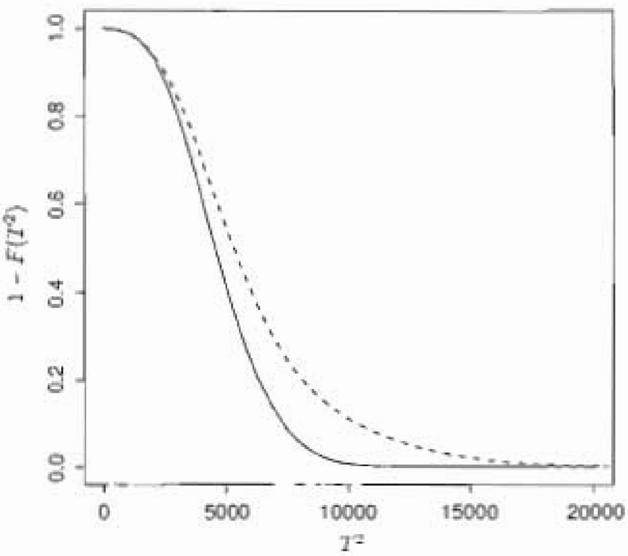

Fig. 7. Cumulative probability of extreme events for fine (solid curve) and rough (dotted curve) grid.

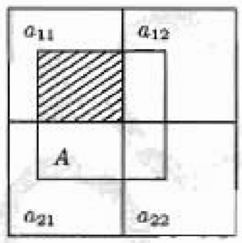

Fig. 9. Rule to select a station to represent weather data within a "big" cell. Here $(i_A, j_A) = (1, 1)$.

cell. A weather station located in the upper left "small" cell having the biggest intersection area with the "big" cell is used to represent weather data for that "big" cell. Fig. 9 illustrates this rule. The mathematical formulation is following. Let A be one of the "big" squares corresponding to cells of the "rough" grid, let a_{ij} be the squares corresponding to the "fine" grid. The index (i_A, j_A) of a weather station corresponding to the square A is defined as follows:

$$\begin{aligned}
s_A &= \max_{i,j} \rho(A \cap a_{ij}) \\
Z_A &= \{(i,j) | \rho(A \cap a_{ij}) = s_A\} \\
Y_A &= \{(i,j) | (i,j) \in Z_A, (i, j-1) \notin Z_A\}, \\
&\quad (i_A, j_A) : (i_A, j_A) \in Y_A, \quad (i_A - 1, j_A) \notin Y_A
\end{aligned}$$

here $\rho(U)$ is the area of the planar set $U \subset R^2$.

Fig. 10 shows the dependence of the burned and patrolled areas when applying the patrolling rules discussed in the Section II-C to grids with cell sizes ranging from 200% to 100% of original size. The figure shows, also, the number of weather stations used for observations and disposition change of those weather stations. Obviously, the dependence of burned area and patrolled area on cell size is non-monotonous. This means that however the general trend shows the system performance is improving with refinement of the grid resolution, an increased resolution may sometimes, also, lead to a downgrade. To comment this counter-intuitive phenomena we would

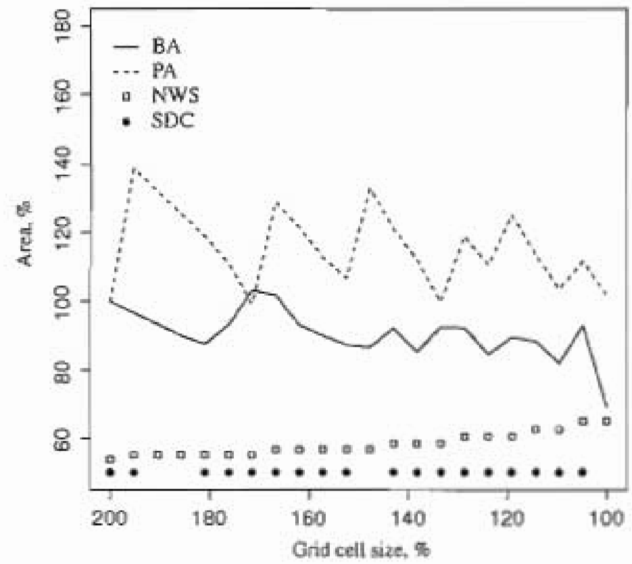

Fig. 10. Dependence of the burned (BA) and patrolled (PA) areas for cell size ranging from 200% to 100% of the original size. The total number of weather stations (NWS) is rescaled and the points when the disposition of weather stations changes (SDC) are shown.

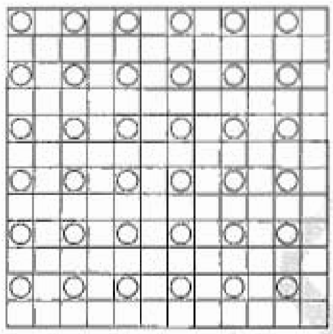

Fig. 11. Selected 36 stations on the 12 × 12 grid, which are subject to switching off.

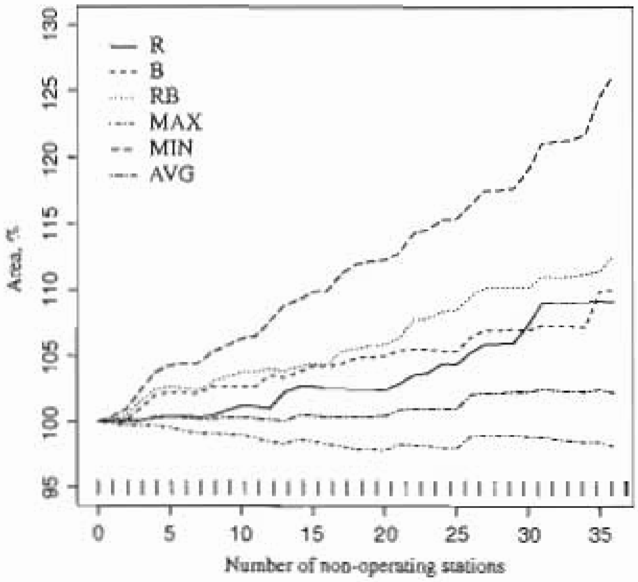

Fig. 12. Dependence of the burned area on the number of non-operating stations for selection of the neighboring substituting cell next to right (R), bottom (B), right-bottom (RB) to the non-operating cell, and based on maximum (MAX), minimum (MIN), and average (AVG) of Nesterov index.

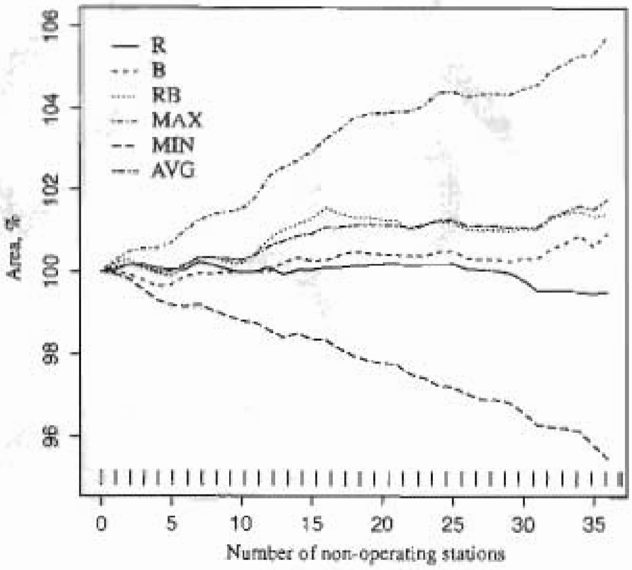

Fig. 13. Dependence of the patrolled area on the number of non-operating stations for selection of the neighboring substituting cell next to right (R), bottom (B), right-bottom (RB) to the non-operating cell, and based on maximum (MAX), minimum (MIN), and average (AVG) of Nesterov index.

emphasize the irregular structure, variable spatial density of weather stations, and step-wise change of their locations (see Fig. 8).

2) Variation of Number of Stations: In Section III-B1, we considered the implicit dependence of the model performance on the number of weather stations and their locations by varying the grid resolution. In this section, we apply a more explicit approach to vary the amount of input data and consider the reduction of number of weather stations just by sequentially switching off some of them. Fig. 11 shows the selected 36 stations on the 12 × 12 grid, which are subject to switching off.

Figs. 12 and 13 show the dependence of burned and patrolled area, respectively, on the number of non-operating stations. Each of the figures shows five curves that correspond to alternative ways to fill the data gap arising from switching off a weather station. We consider the usage of weather data from a neighboring station (next to the right, next down, next right, and down—together further referred to as *neighboring cells*) as well as using minimum, maximum, and average fire danger index calculated for neighboring cells. Using the minimum of Nesterov index leads to the increase in burned area and decrease in patrolled area, while using the maximum of Nesterov index leads to decrease in burned area and increase in patrolled area.

3) Optimization of Stations' Locations: In addition to consideration of different grid resolutions of weather data and the value of individual weather stations for overall performance of the entire system discussed in Sections III-B1 and III-B2 we proceed with the consideration of optimal locations of the stations. We consider a network of weather stations supplying weather data on a "rough" grid, and we increase the number

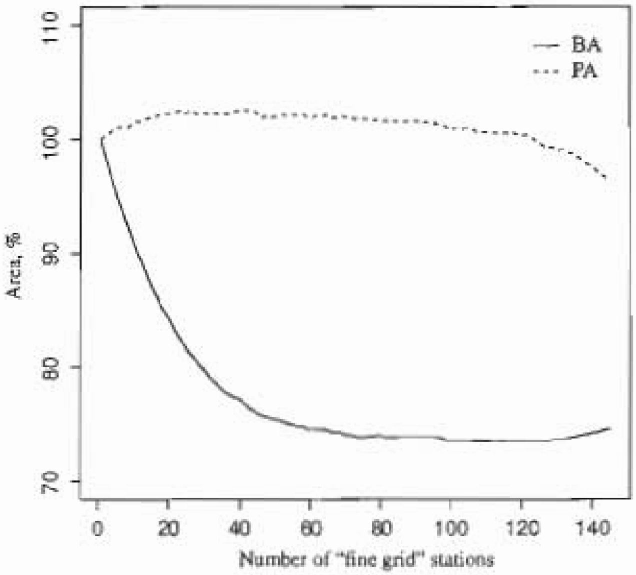

Fig. 14. Dependence of the burned (BA) and patrolled (PA) areas on the number of added weather stations. Minimization of burned area.

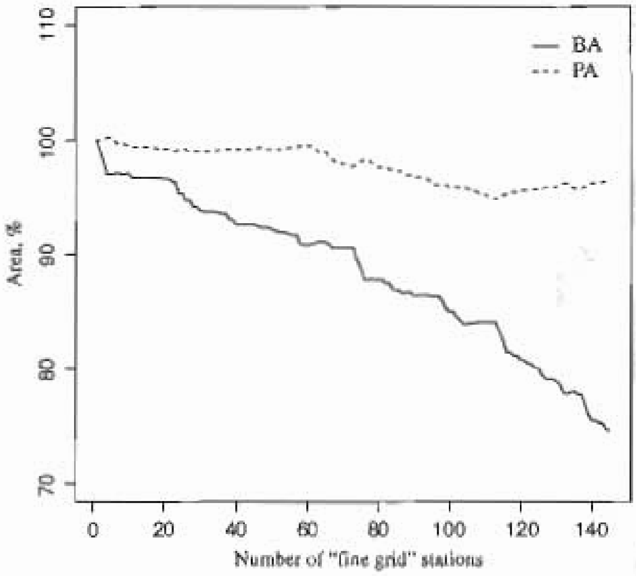

Fig. 15. Dependence of the burned (BA) and patrolled (PA) areas on the number of added weather stations. Minimization of patrolled area.

of weather stations in most critical "small" cells. The term *critical* means that the contribution of a particular cell to the total burned area (or patrolled area) is maximal. The burned and patrolled areas are recalculated for modified (improved) data set and, then, the procedure is repeated to select the next cell where better information should be used. Since we do not specify any further technical details, the suggested approach may, also, be considered as a model of combination of rough and fine data sets representing the integration of two systems, one of which provides relatively rough information at a low cost and the other system supplies relatively costly, but more precise information (this could be, e.g., satellite observations and in-situ measurements).

Fig. 14 illustrates the dependence of burned and patrolled areas on the number of weather stations located in cells with maximum burned area estimation. Fig. 15 illustrates the same for cells with maximum patrolled area estimation. The important point to emphasize here is that the introduction of a relatively small number of more precise stations in critical areas could immensely improve the overall performance of the system. So Fig. 14 shows that 30 precise stations covering only 20% of the territory could provide an improvement of about 20% of initial burned area, that is nearly 75% of the improvement possible (by placing the weather stations everywhere). The optimal combination should take into account the tradeoff between the costs for improved information and possible losses caused by fire.

IV. Discussion and Conclusion

In this paper, we first presented a sketchy model of forest fire fighting to quantitatively assess burned areas and patrolling efforts. The simulation-based versiou of the model delivers more accurate results as to average values and provides useful information on distributions of important characteristics of fires. This approach allows us, also, to investigate correlations between key parameters, e.g., average Nesterov index and expected burned area. The stochastic approach promotes the inclusion of parameters such as wind speed and variable fire spread rate. However, in this case the simulations are rather computationally expensive, and this should be taken into account when building efficient models using large number of parameters.

In Section III-B, we analyzed the impact of data quality on the forest fires management model. However, for the purposes of generality, we did not specify the way the weather parameters are measured nor the sensitivity of these measurements to other factors. Some papers related to the analysis of remote observation systems performance, depending on measurement method and current measuring conditions, include [13]–[16] and have carried out this type of analysis.

The forest fire detection model presented in this paper is based on the Nesterov fire danger index. The Nesterov index is a natural candidate for simplified fire danger rating, since it is an easily computable function of a few parameters. However, the model can be modified to use similar indices, such as KBDI (see, e.g., [6]) or more sophisticated systems (e.g., Canadian FFWI, see [1]). The comparison of the sensitivity of different fire danger rating systems to the quality of weather data with the application to the model presented in this paper could be an interesting direction for further research.

We assume that Nesterov index is suitable for the local conditions under consideration. Using more sophisticated systems for the analysis would require much more detailed data and additional efforts to get the data, which are usually not freely available. Although the presented analysis is quite basic, we believe that the conclusions will still remain in force and that other indices would produce the results in the same direction, although not necessarily to the same extent.

In this paper, we presented a methodology to assess the beuefits of improved weather observations with the application to forest fire management. The results of the modeling could be refined by taking into account other parameters important for forest fire management, such as e.g. fuel load in the forest, type of the forest, age of the forest, resources availability in terms of fire fighters and equipment for fire extinguishing, aircrafts, and fuel for forest patrols. Further research in this direction could contribute to the elaboration of procedures and data standards within national and global forest fire risk management systems, including fire danger rating and fire detection.

Our results show that an increase in quality of weather information generally leads to improved performance of fire fighting. However, in some cases, where an underlying data set has an irregular structure, the increased resolution may downgrade the performance of the system. This phenomenon may be considered as an important design issue for the forest fire risk management system.

The analysis of the optimal stations' location problem shows that the total system performance can be optimized, and, at the same time, the costs for implementation, operation, and maintenance can be reduced thanks to better overall systems design. A possible interpretation of this result in terms of integration of two systems ("precise-expensive" and "rough-cheap") leads to the conclusion that an optimal combination of systems (SoS) is able to deliver a significant improvement in the overall system's performance as well as improved cost-effectiveness. This conclusion is close to the Global Earth Observation System of Systems concepts, which imply benefits from integration of different observation systems. Further research should be performed in order to evaluate the properties of a wider and more comprehensive SoS covering more socio-economic benefit areas of Global Earth Observations.

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REFERENCES

[1] C. E. Van Wagner, "Development and structure of the Canadian Forest Fire Weather Index System," Canadian Forestry Service, Ottawa, ON, Canada, Forestry Tech. Rep. 35, 1987.

[2] K. Satoh, S. Weiguo, and K. T. Yang, "A study of forest fire danger prediction system in Japan," *DEXA*, vol. 00, pp. 598–602, 2004.

[3] *Monitoring and Forecasting of Forest Fires. General Requirements* (in Russian), GOST R 22.1.09-99, The State Standard of Russian Federation, 1999.

[4] V. Nesterov, *Forest Fires and Methods of Fire Risk Determination* (in Russian). Moscow: Goslesbumizdat, 1949.

[5] S. Malevsky-Malevich, E. Molkentin, E. Nadyozhina, and O. Shklyarevich, "An assessment of potential change in wildfire activity in the Russian boreal forest zone induced by climate warming during the twenty-first century," *Climatic Change*, vol. 86, no. 3, pp. 463–474, 2008.

[6] G. Buchholz and D. Weidemann, "The use of simple fire danger rating systems as a tool for early warning in forestry," *Int. Forest Fire News*, no. 23, pp. 32–36, 2000.

[7] J. A. Goff and S. Gratch, "Low-pressure-properties of water from −160 to 212 F," *Trans. Amer. Soc. Heat. Ventilating Eng.*, vol. 52, pp. 95–122, 1946.

[8] A. Barenbrug, *Psychrometry and Psychrometric Charts*, 3rd ed. Cape Town: Chamber of Mines of South Africa, 1974.

[9] Federal Forest Service of Russian Federation, **<PLEASE PROVIDE COMPANY LOCATION.>** "Instructions for detection and fighting of forest fires (Part I). Order No. 100," (in Russian) Jun. 1999.

[10] S. Venevsky, K. Thonicke, S. Sitch, and W. Cramer, "Simulating fire regimes in human-dominated ecosystems: Iberian peninsula case study," *Global Change Biology*, vol. 8, no. 10, pp. 984–998, 2002.

[11] H. P. Telitsyn, *Lesnye Pozhary, Ich Preduprezhdenie I Bor'ba S Nimi V Khabarovskom Krae* (in Russian). Khabarovsk: DALNIILKH, 1988.

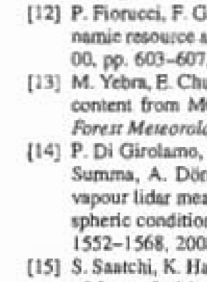
[12] P. Fiorucci, F. Gaetani, R. Minciardi, R. Sacil, and E. Trasforini, "Dynamic resource allocation for forest fire risk management," *DEXA*, vol. 00, pp. 603–607, 2004.

[13] M. Yebra, E. Chuvieco, and D. Riaño, "Estimation of live fuel moisture content from MODIS images for fire risk assessment," *Agricultural Forest Meteorology*, vol. 148, no. 4, pp. 523–536, 2008.

[14] P. Di Girolamo, A. Behrendt, C. Kiemle, V. Wulfmeyer, H. Bauer, D. Summa, A. Dörnbrack, and G. Ehret, "Simulation of satellite water vapour lidar measurements: Performance assessment under real atmospheric conditions," *Remote Sensing Environment*, vol. 112, no. 4, pp. 1552–1568, 2008.

[15] S. Saatchi, K. Halligan, D. G. Despain, and R. L. Crabtree, "Estimation of forest fuel load from radar remote sensing," *IEEE Trans. Geosci. Remote Sensing*, vol. 45, no. 6, pp. 1726–1740, Jun. 2007.

[16] R. Lasaponara and A. Lanorte, "Remotely sensed characterization of forest fuel types by using satellite ASTER data," *Int. J. Appl. Earth Observation Geoinform.*, vol. 9, no. 3, pp. 225–234, 2007.



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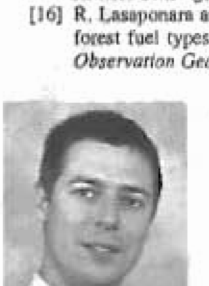

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ACTA HYDROLOGICA SLOVACA

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ANALÝZA ZMIEN ŠTATISTICKÝCH CHARAKTERISTÍK DENNÝCH ÚHRNOV ZRÁŽOK NA STANICI HURBANOVO V RÔZNYCH OBDOBIACH ČASŤ II. FREKVENČNÁ ANALÝZA

Ján Pekár, Pavla Pekárová, Juraj Olbřímek, Pavol Miklánek

V druhej časti štúdie sú pomocou histogramov rozdelenia početností, empirických čiar prekročenia a frekvenčných čiar zrážkových úhrnov ako aj štatistických testov identifikované zmeny rozdelenia početností denných zrážkových úhrnov zo stanice Hurbanovo za rôzne obdobia (60-ročné obdobia, 30-ročné obdobia pre zimno-jarné i letno-jesenné sezóny). Štatisticky nebol potvrdený častejší výskyt vysokých denných zrážkových úhrnov (nad 51,2 mm), ani častejší výskyt extrémne dlhých období sucha v trvaní nad 50 dní bez zrážok. Pokles ročných zrážkových úhrnov z posledného tridsaťročia je zapríčinený menej častým výskytom denných zrážkových úhrnov v rozmedzí 0,4 až 25,6 mm. Zvýšený výskyt lesných požiarov a požiarov v poľnohospodárstve v SR tesne kopíruje výskyt suchých období na stanici Hurbanovo.

KĽÚČOVÉ SLOVÁ: atmosférické zrážky, extremalita, frekvenčná analýza

ANALYSIS OF THE STATISTICAL CHARACTERISTICS OF DAILY PRECIPITATION AT HURBANOVO IN DIFFERENT PERIODS: PART II. **FREQUENCY ANALYSIS.** In the second part of the study we identified the changes in daily precipitation distribution at Hurbanovo observatory in different periods (60-years periods, 30-years periods for winter-spring and summer-autumn seasons) using histograms, empirical exceedance curves and frequency curves of daily precipitation. Statistical analysis did not confirm neither more frequent occurrence of high daily precipitation (over 51.2 mm per day) nor more frequent occurrence of long dry periods (more than 50 days without precipitation). The decrease of annual precipitation in last 30-years period is due to less frequent occurrence of daily precipitation depths between 0.4 to 25.6 mm. The increased number of forest and field fires in SR correlates very closely with occurrence of the dry periods at Hurbanovo observatory.

KEY WORDS: precipitation, extremality, frequency analysis

Úvod

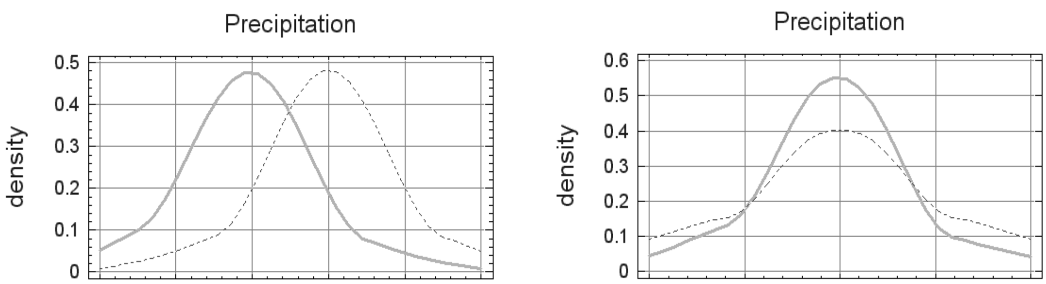
Vychádzajúc z teórie zvyšovania sa teploty vzduchu v dôsledku zvýšených koncentrácií skleníkových plynov v atmosfére sa vo všeobecnosti očakáva, že bude dochádzať k zvyšovaniu sa extremality hydrologických a klimatických radov. Podľa záverov IPCC by mal vplyvom zvýšenej teploty vzduchu rásť počet extrémnych zrážkových udalostí a povodní a súčasne by mali klesať minimálne prietoky v tokoch. Tento jav je pre zrážkové úhrny znázornený na obr. 1. Ľavý obrázok schematicky znázorňuje posun čiary hustoty pravdepodobnosti k vyšším hodnotám. Pravý obrázok znázorňuje situáciu, keď nedôjde k zvýšeniu priemerov, ale k zvýšeniu variability radu zrážok – bude sa vyskytovať viac nízkych a viac vysokých zrážkových úhrnov. Vo všeobecnosti prevláda názor, že k tomuto javu už po roku 1990 došlo. Cieľom druhej časti štúdie je potvrdiť túto hypotézu frekvenčnou analýzou radu denných úhrnov zrážok v stanici Hurbanovo za rôzne podobdobia rokov 1901–2006.

Stanica Hurbanovo (predtým Ógyalla) je reprezentatívnou stanicou pre oblasť Podunajskej nížiny (Petrovič a kol., 1960). Rad denných zrážkových úhrnov z tejto stanice je spracovaný už od roku 1872 a v posledných rokoch bol analyzovaný vo viacerých štúdiách (pozri napr. Šamaj a kol. 1985; Melo, 2003; Gaál a Lapin, 2002; Gaál a kol., 2005; Lapin 2004; Lapin a Faško, 1998; Lapin a kol., 2001, 2003; Lapin a Damborská, 2007). Mesačné úhrny z tohto radu počnúc rokom 1876 sme prevzali z práce Petrovič a kol. (1960), rad denných úhrnov za obdobie 1901–2006 nám bol poskytnutý prof. Lapinom pre potreby projektu GEOBENE.

Analýza zmien histogramov, empirických čiar prekročenia a frekvenčných čiar denných úhrnov zrážok za rôzne časové obdobia

Pri štatistickej analýze denných zrážkových úhrnov na stanici Hurbanovo sme využili bežné štatistické metódy naprogramované v softvéroch EXCEL, STAGRAPHICS, ako aj špeciálne softvéry CTPA (Procházka a kol., 2001), AnClim (Štepánek, 2003), FreqCurves (Bulletin 17b, 1982) a BestFit. Na obr. 1 sú zobrazené histogramy rozdelenia početností denných úhrnov zrážok s krokom 1 mm pre dve 60-ročné obdobia zo zrážok nad 0 mm. Početnosti výskytu zrážok v jednotlivých triedach sú predelené počtom spracovaných rokov, čiže graf znázorňuje dlhodobý priemerný počet výskytu daných zrážkových úhrnov v jednom roku – dlhodobý priemerný ročný histogram. (Kvôli zjednodušeniu spracovania údajov sme z radov vylúčili 29. februáre a pracovali sme s 365 denným rokom.) Os y je v záujme lepšej vizualizácie transformovaná logaritmickou funkciou. Histogramy analyzovaných dvoch období (1901–1960 a 1947–2006) sa vizuálne výraznejšie nelíšia.

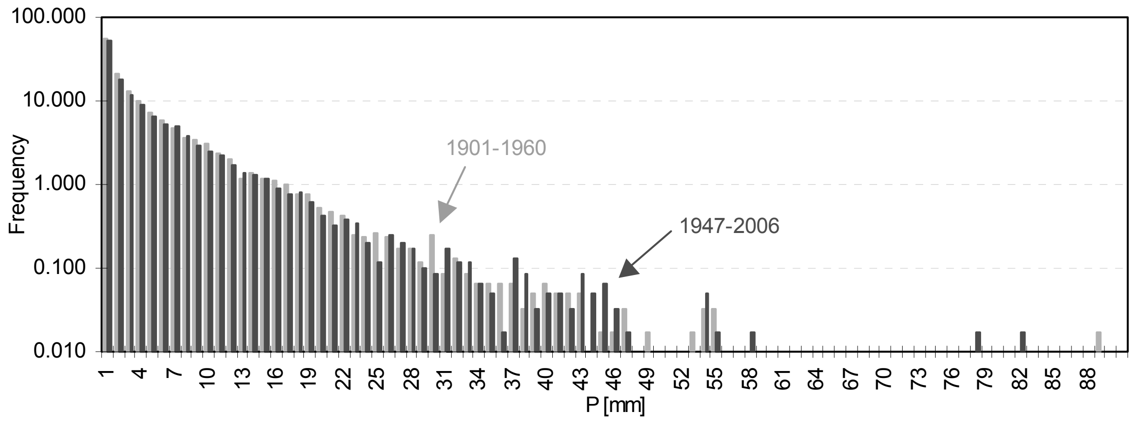
V tabuľke 1 sú uvedené početnosti výskytov jednotlivých zrážkových úhrnov pre tri rôzne obdobia. Z tabuľky 1 vyplýva, že v celom období 1901–2006 sa na stanici Hurbanovo vyskytlo v roku v priemere 191,8 dní bez zrážok a 136,8 dní so zrážkami nad 0 mm. Z toho až 52,8 dní je so zrážkami od 0,1 do 1 mm. V priemere v Hurbanove iba 84,4 dní v roku je dosiahnutý zrážkový úhrn nad 1mm. V období 1947–2006 bol dosiahnutý zrážkový úhrn nad 1 mm o 7 dní menej v porovnaní s predchádzajúcim obdobím (1901–1960). Vysoké zrážkové úhrny nad 50 mm sa nevyskytli častejšie.



a) **b)**

Obr. 1. Možné hypotetické zmeny a) priemeru a b) variability starého (hrubšia čiara) a nového obdobia pre zrážky podľa IPCC (2001).

Fig. 1. Possible hypotetic changes in a) mean and b) variability of precipitation totals, according to IPCC (2001).



Obr. 2. Priemerný počet dní v roku so zrážkovým úhrnom P nad 0 mm pre denné úhrny zrážok, obdobie 1901–1960 (svetlé stĺpce) a 1947–2006 (tmavé stĺpce).

Fig. 2. Average number of days in the year with daily precipitation depth P over 0 mm, period 1901–1960 (light columns) and 1947–2006 (dark columns).

Tabuľka 1. Priemerný ročný počet dní bez zrážok (PDBZ), počet dní so zrážkami (PDSZ) a počet dní so zrážkami nad 0 mm (PDSZ-0) za tri obdobia. Priemerný počet dní so zrážkami v jednotlivých triedach za tri rôzne obdobia

Table 1. Average annual number of days without precipitation (PDBZ), number of days with precipitation (PDSZ) and number of days with precipitation depth over 0 mm (PDSZ-0) in three periods. Average number of days with precipitation in individual classes in three different periods

[mm}	**1901-2006**	1901-1960	1947-2006	[mm}	**1901-2006**	1901-1960	1947-2006
PDBZ	**191.8**	192.5	188.8	10.1-11	**2.30**	2.30	2.27
PDSZ	**173.2**	172.5	176.2	11.1-12	**1.86**	2.05	1.73
PDSZ-0	**136.8**	141.9	132.0	12.1-13	**1.26**	1.18	1.38
0 mm	**36.4**	30.6	44.2	13.1-14	**1.34**	1.35	1.28
0.1-1	**52.8**	54.3	52.1	14.1-15	**1.18**	1.15	1.20
1.1-2	**19.5**	20.8	18.4	15.1-16	**1.04**	1.12	0.90
2.1-3	**12.3**	12.8	11.7	16.1-17	**0.91**	1.02	0.77
3.1-4	**9.67**	10.2	9.00	17.1-18	**0.79**	0.78	0.82
4.1-5	**7.02**	7.13	6.60	18.1-19	**0.68**	0.75	0.62
5.1-6	**5.62**	5.88	5.30	19.1-20	**0.48**	0.52	0.43
6.1-7	**4.87**	4.83	4.87	20.1-50	**3.443**	3.533	3.350
7.1-8	**3.75**	3.67	3.85	50.1-80	**0.075**	0.083	0.100
8.1-9	**3.18**	3.52	2.87	80.1-90	**0.019**	0.017	0.017
9.1-10	**2.70**	3.00	2.48	spolu	**365**	365	365

Empirické čiary prekročenia denných zrážkových úhrnov pre dve 60-ročné obdobia

Pri ďalších analýzach zrážkové udalosti do 0,1 mm nebudeme brať do úvahy. Základné štatistické spracovanie šiestich 30-ročných radov denných zrážkových úhrnov nad 0,1 mm zo stanice Hurbanovo je prezentované v tabuľkách 2 až 4. Až na fakt, že ročné zrážkové úhrny na stanici Hurbanovo klesajú, k zmenám priemerného úhrnu jednej zrážkovej udalosti (vzhľadom na menší počet zrážkových udalostí – menej často prší) nedochádza ani v letno-jesennom, ani v zimno-jarnom období. Dlhodobý priemerný denný úhrn zrážok (nad 0,1 mm) je 4,47 mm, v letno-jesennom období je 5,4 mm a v zimno-jarnom 3,71 mm. Porovnaním hodnôt percentilov 0,01 a 0,1 v tabuľkách 2-4 vyplýva, že posledné 30-ročné obdobie sa nelíši od predchádzajúcich 30-ročných období. Hodnotu percentilu 0,01=80,49 mm môžeme interpretovať ako odhad 100 ročného úhrnu zrážok.

Na obr. 3a sú vykreslené empirické čiary prekročenia (inverzné distribučné funkcie) denných zrážkových úhrnov nad 0,1mm z údajov za dve obdobia 1901–1960 a 1947–2006 pre zimno-jarnú a pre letno-jesennú sezónu. Na obrázku je vykreslený aj interval, v ktorom by sa mohol nachádzať denný zrážkový úhrn s dobou opakovania 1000 rokov pre jednotlivé sezóny.

Pre presnejší odhad 100-, 500- a 1000-ročných dôb opakovania extrémne vysokých úhrnov zrážok sme zostrojili teoretické distribučné funkcie maximálnych denných úhrnov zrážok v roku (P_{max}) (Lapin a Damborská, 2007; Stehlová a kol., 2001). Pri výbere vhodného typu teoretickej distribučnej funkcie sme použili softvér BestFit a FreqCurves. Z 19-tich typov rozdelení sme na základe viacerých testov (Chi-kvadrat testu, K-S testu a A-D testu) vybrali ako najvhodnejšie trojparametrické log-Pearsonovo rozdelenie III. typu (Bulletin 17b, 1982). Teoretické čiary prekročenia P_{max} maximálnych ročných zrážkových úhrnov sme zostrojili osobitne pre letno–jesennú a pre zimno–jarnú sezónu pre dve obdobia: 1901–1960 a 1947–2006. Na obr. 3b je uvedený príklad teoretických čiar pre letno-jesennú sezónu pre obe uvedené obdobia.

Porovnanie zmien frekvenčných čiar rôznych období

Jednotlivé obdobia sme ďalej porovnali pomocou frekvenčných čiar denných zrážkových udalostí (čiar rozdelenia početnosti výskytu denných zrážkových udalostí v jednotlivých triedach). Čiary rozdelenia početnosti výskytu zrážkových udalostí sme spracovali osobitne pre dve 60-ročné obdobia 1901–1960 a 1947–2006 a pre 30-ročné obdobia pre:

1. každý mesiac (obr. 4),
2. pre zimno-jarné a letno-jesenné obdobie (obr. 5a-b),
3. pre celý rok (obr. 6).

Pre rozdelenie zrážkových úhrnov v desatinách mm do jednotlivých tried (os x) sme použili funkciu 2^n pre n=0, 1, 2, ... , 10. Takéto rozdelenie jednotlivých tried zabezpečí dostatočný počet prvkov v jednotlivých triedach a umožňuje vizuálne porovnanie na grafoch.

Tabuľka 2. Základné štatistické charakteristiky denných zrážkových úhrnov na stanici Hurbanovo za rôzne 30-ročné obdobia, percentily 0,01% až 90%. Celý rok

Table 2. Basic statistical characteristics of daily precipitation at Hurbanovo in different 30-years periods, percentiles 0.01% to 90%, the whole year (1st row – mean annual depth over 0.1 mm, 2nd row – number of days over 0.1 mm, 3rd row – mean depth for one day)

	1901-1930	1916-1945	1931-1960	1946-1975	1961-1990	1976-2005	**1901-2006**
Prm. ročný úhrn nad 0.1mm	584.4	580.7	570.2	545.7	521.5	526.3	**556.9**
počet udalostí nad 0.1 mm	3964	4038	3834	3617	3568	3524	**13200**
Priemer jednej zr. udalosti	4.42	4.31	4.46	4.53	4.39	4.48	**4.47**
Percentil 0,01	75.29	75.03	54.09	69.27	65.75	73.17	**80.49**
Percentil 0,1	42.44	42.18	46.33	49.34	42.99	45.08	**45.50**
Percentil 1	27.93	28.80	29.37	29.78	28.07	30.63	**29.50**
Percentil 2	21.67	22.03	24.20	23.64	22.27	22.90	**22.70**
Percentil 5	15.99	16.12	16.80	16.50	16.07	16.00	**16.20**
Percentil 10	11.20	11.00	11.50	11.50	11.10	11.37	**11.40**
Percentil 30	4.80	4.60	4.70	4.80	4.80	4.80	**4.80**
Percentil 50	2.30	2.00	2.10	2.20	2.20	2.30	**2.20**
Percentil 70	1.00	0.90	0.90	0.90	0.90	0.90	**0.90**
Percentil 90	0.30	0.30	0.30	0.30	0.30	0.30	**0.30**

Tabuľka 3. Základné štatistické charakteristiky denných zrážkových úhrnov na stanici Hurbanovo za rôzne 30-ročné obdobia, percentily 0,01% až 90%. Letno-jesenná sezóna

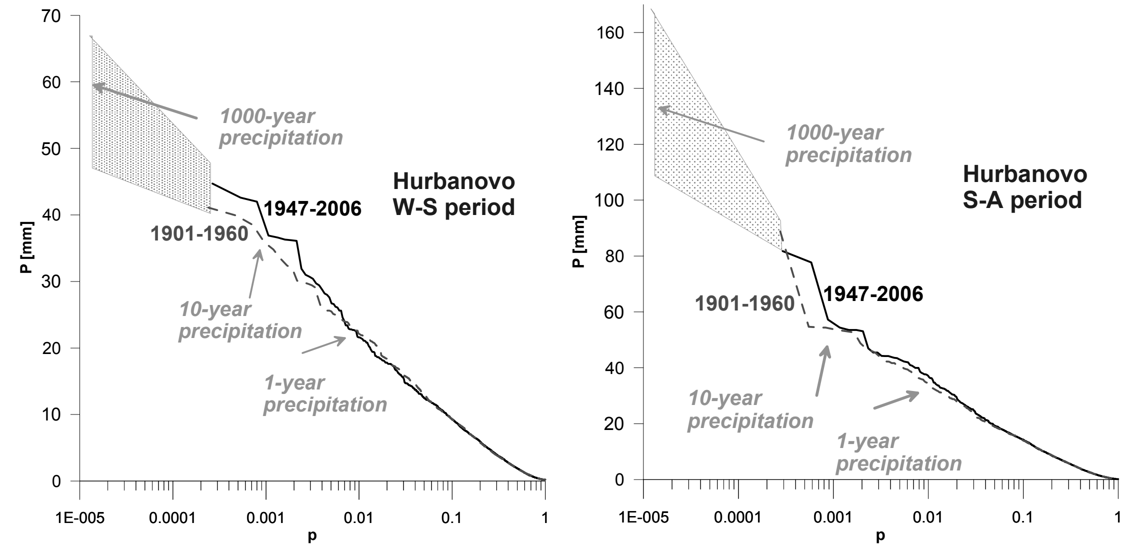
Table 3. Basic statistical characteristics of daily precipitation at Hurbanovo in different 30-years periods, percentiles 0.01% to 90%, the summer-autumn season (1st row – mean annual depth over 0.1 mm, 2nd row – number of days over 0.1 mm, 3rd row – mean depth for one day)

Letno-jesenné obdobie	1901-1930	1916-1945	1931-1960	1946-1975	1961-1990	1976-2005	**1901-2006**
Prm. ročný úhrn nad 0.1mm	325.67	323.46	326.30	313.44	295.62	304.57	**317.90**
počet udalostí nad 0.1 mm	1857	1845	1776	1709	1702	1690	**6235.00**
Priemer jednej zr. udalosti	5.26	5.26	5.51	5.50	5.21	5.41	**5.40**
Percentil 0,01	82.47	82.51	54.26	73.72	72.00	77.66	**84.44**
Percentil 0,1	52.99	49.72	53.21	53.83	43.78	54.75	**53.60**
Percentil 1	31.14	32.31	34.85	37.00	32.40	36.33	**34.53**
Percentil 2	24.30	28.80	29.20	29.56	25.70	28.80	**27.93**
Percentil 5	18.20	18.78	19.63	20.00	19.00	18.96	**19.10**
Percentil 10	13.44	13.86	14.50	14.70	14.09	13.71	**14.10**
Percentil 30	5.90	5.70	5.90	5.80	5.80	6.00	**5.90**
Percentil 50	2.90	2.60	2.50	2.60	2.60	2.70	**2.70**
Percentil 70	1.20	1.10	1.10	1.10	1.10	1.10	**1.10**
Percentil 90	0.30	0.30	0.30	0.30	0.30	0.30	**0.30**

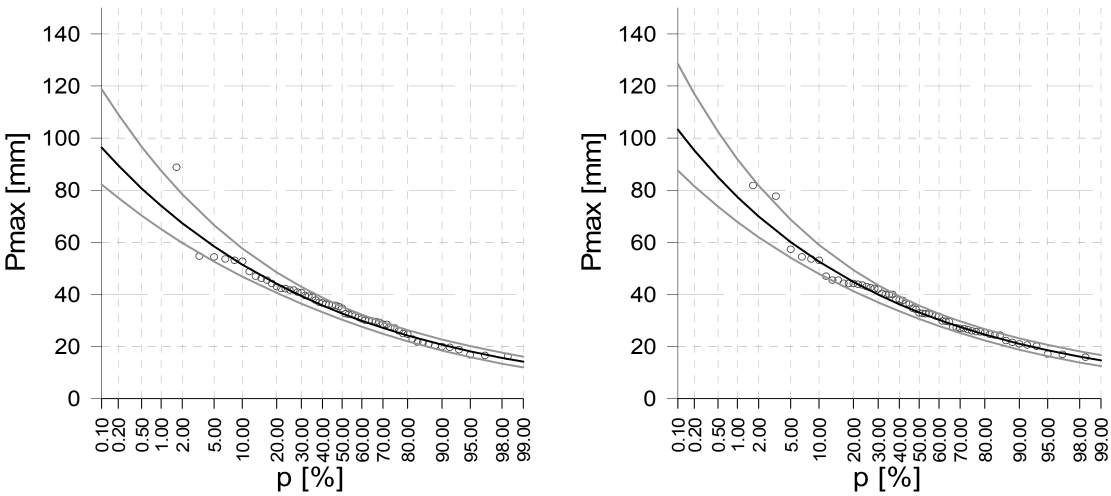
Tabuľka 4. Základné štatistické charakteristiky denných zrážkových úhrnov na stanici Hurbanovo za rôzne 30-ročné obdobia, percentily 0,01% až 90%. Zimno-jarná sezóna

Table 4. Basic statistical characteristics of daily precipitation at Hurbanovo in different 30-years periods, percentiles 0.01% to 90%, the winter-spring season (1st row – mean annual depth over 0.1 mm, 2nd row – number of days over 0.1 mm, 3rd row – mean depth for one day)

Zimno-jarné obdobie	1901-1930	1916-1945	1931-1960	1946-1975	1961-1990	1976-2005	**1901-2006**
Prm. ročný úhrn nad 0.1mm	279.47	276.60	261.04	245.71	242.94	238.73	**256.74**
počet udalostí nad 0.1 mm	2215	2300	2170	2011	1963	1926	**7335**
Priemer jednej zr. udalosti	3.79	3.61	3.61	3.67	3.71	3.72	**3.71**
Percentil 0,01	50.13	39.16	34.17	42.48	42.48	43.20	**46.83**
Percentil 0,1	39.88	33.31	29.73	31.88	37.09	36.62	**38.00**
Percentil 1	24.24	22.60	21.96	22.59	22.54	22.30	**22.70**
Percentil 2	18.67	19.50	18.72	17.88	18.03	18.15	**18.53**
Percentil 5	13.73	13.41	12.90	12.70	13.20	12.98	**13.10**
Percentil 10	9.40	9.30	9.40	9.50	9.28	9.20	**9.40**
Percentil 30	4.00	3.90	3.80	3.90	4.00	4.10	**4.00**
Percentil 50	1.90	1.70	1.80	1.90	1.90	2.00	**1.90**
Percentil 70	0.90	0.80	0.80	0.80	0.80	0.80	**0.80**
Percentil 90	0.30	0.30	0.30	0.30	0.30	0.30	**0.30**

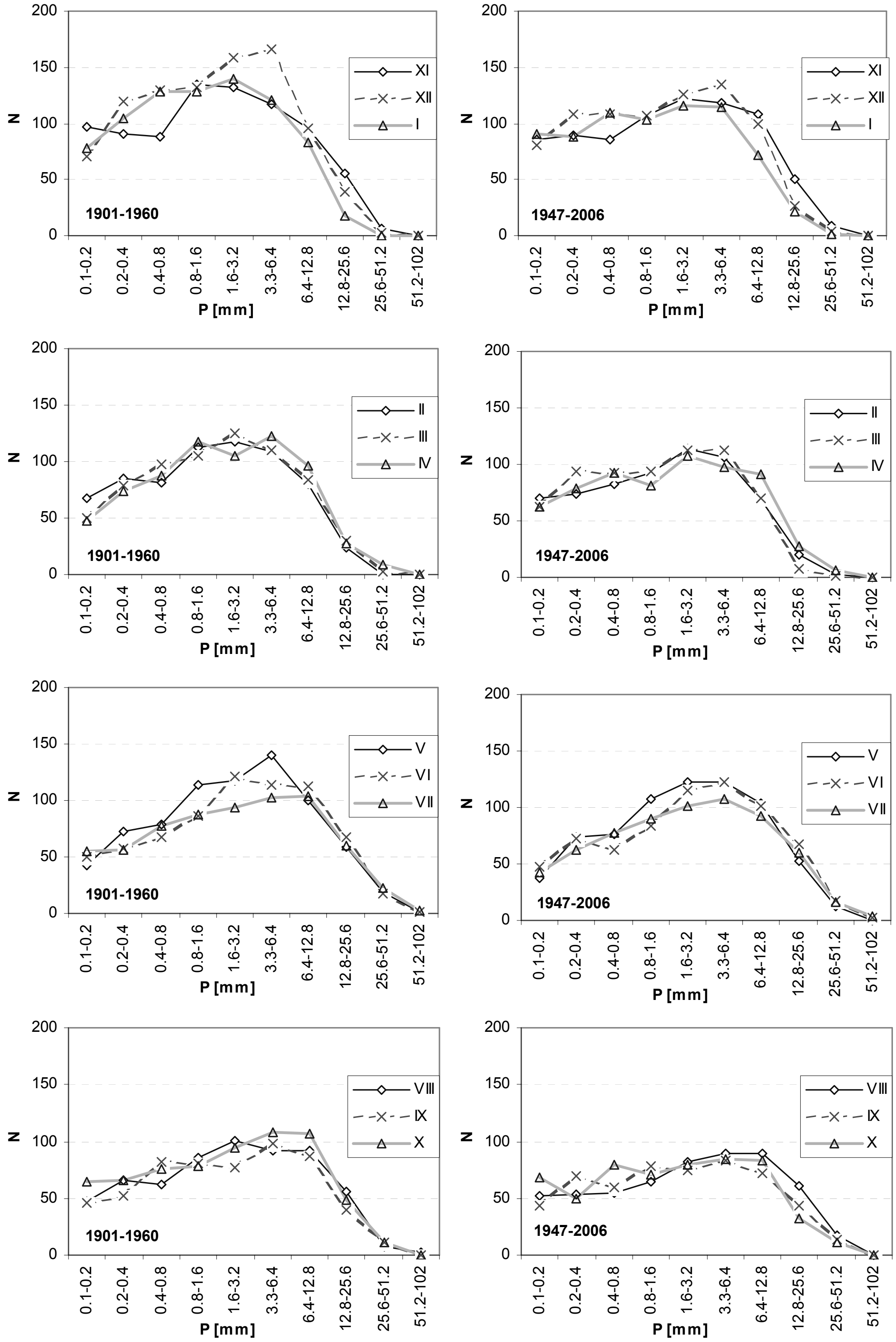


a)

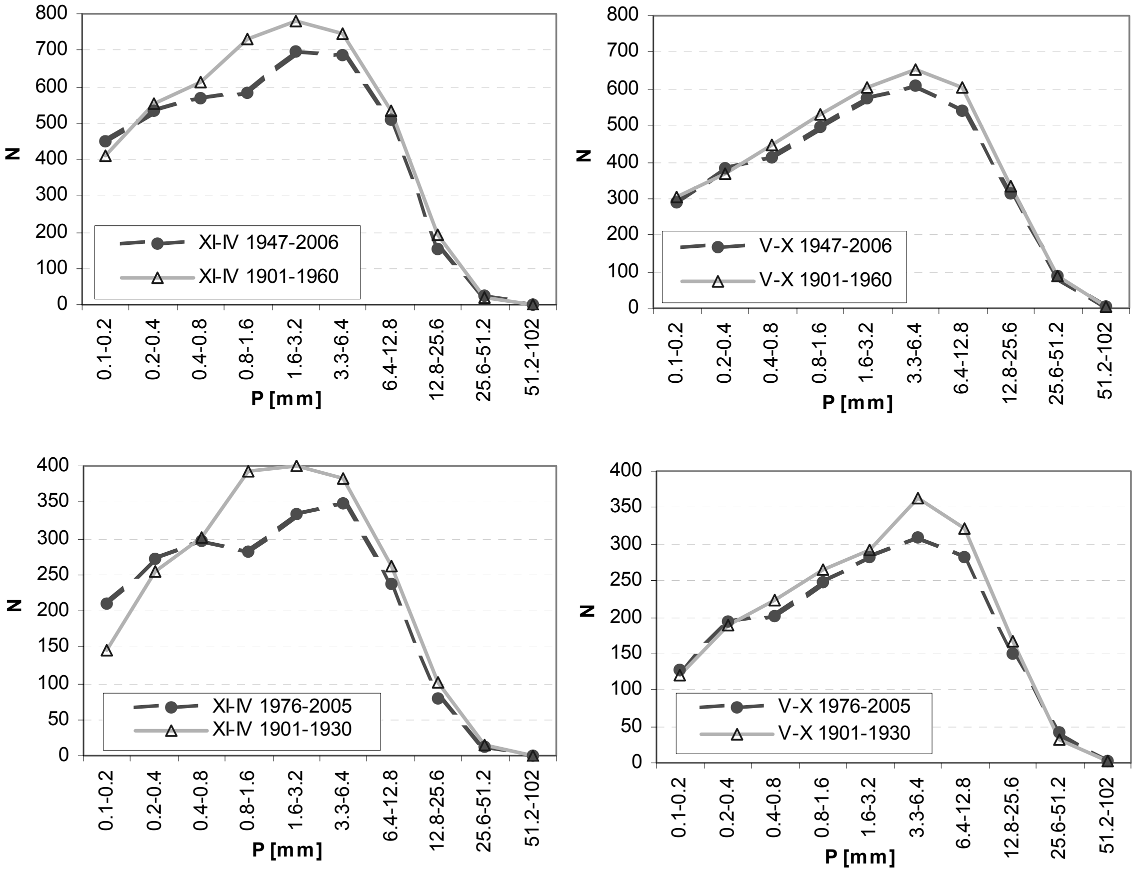


b) 1901–1960 1947–2006

Obr. 3.
a) Empirické čiary prekročenia denných zrážkových úhrnov (P) zo stanice Hurbanovo za dve obdobia 1901–1960 a 1947–2006 pre zimno–jarnú sezónu (vľavo) a pre letno–jesennú sezónu (vpravo), p– pravdepodobnosť, P–denný zrážkový úhrn.
b) Teoretické log-Pearsonove čiary III. typu prekročenia maximálnych denných zrážkových úhrnov v roku (P_{max}), Hurbanovo, za letno-jesennú sezónu, obdobie 1901–1960 a 1947–2006, P–denný zrážkový úhrn [mm], p- pravdepodobnosť [%], 5% a 95% intervaly spoľahlivosti.
Fig. 3.
a) Empirical exceedance curves of daily precipitation at Hurbanovo in two different periods 1901–1960 a 1947–2006 for the winter–spring season (left) and the summer–autumn season (right).
b) Theoretical log-Pearson type III exceedance curves of maximal daily precipitation at Hurbanovo in summer–autumn season within 1901–1960 and 1947–2006 periods, 5% a 95% confidence intervals.



Obr. 4. Porovnanie frekvenčných čiar denných úhrnov zrážok zo stanice Hurbanovo pre jednotlivé mesiace za dve 60-ročné časové obdobia: 1901–1960 (vľavo) a 1947–2006 (vpravo).
Fig. 4. Comparison of frequency curves of daily precipitation at Hurbanovo in individual months for two 60-years periods: 1901–1960 (left) and 1947–2006 (right).

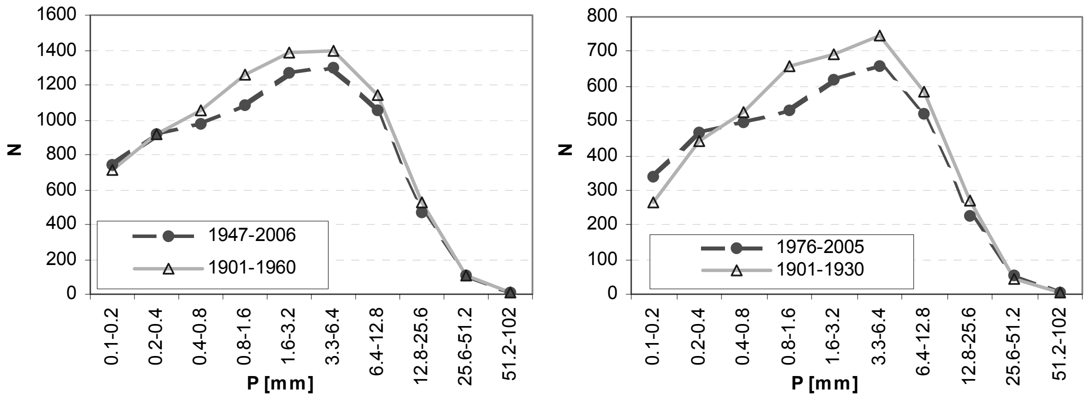


a)

b)

Obr. 5. Porovnanie frekvenčných čiar denných úhrnov zrážok zo stanice Hurbanovo pre zimno-jarnú (november až apríl - XI-IV) a letno-jesennú (máj až október - V-X) sezónu. a) 60-ročné obdobia; b) 30-ročné obdobia.

Fig. 5. Comparison of frequency curves of daily precipitation at Hurbanovo in the winter-spring season (November to April - XI-IV) and the summer-autumn season (May to October - V-X), a) 60-years periods; b) 30-years periods.



a) b)

Obr. 6. Porovnanie frekvenčných čiar denných úhrnov zrážok zo stanice Hurbanovo pre celý rok. a) 60-ročné obdobia; b) 30-ročné obdobia.

Fig. 6. Comparison of frequency curves of daily precipitation at Hurbanovo for the whole year a) 60-years periods; b) 30-years periods.

Z vizuálneho porovnania čiar rozdelenia početnosti (frekvenčných čiar) na obr. 5-6 vyplýva, že v období 1947–2006 došlo k podstatnému zníženiu počtu zrážkových udalostí od 0,8 do 25,6 mm. Počet maximálnych zrážkových úhrnov sa nezmenil v zimno-jarnej sezóne. V letno-jesennej sezóne v poslednom tridsaťročí bol zaznamenaný veľmi mierny nárast počtu denných zrážkových úhrnov v intervale od 25,6 po 51,2 mm. Štatisticky nebol preukázaný nárast počtu maximálnych zrážkových udalostí nad 51,2 mm. V prípade minimálnych zrážkových udalostí došlo k nárastu ich počtu, pri zrážkových úhrnoch od 0,0 do 0,2 mm o viac ako tri udalosti ročne. Tieto nízke hodnoty nemajú väčšiu váhu, nakoľko takéto nízke zrážkové udalosti nemuseli byť v minulosti zaznamenané. Z tohoto dôvodu sme zrážkové úhrny pod 0,1 mm z hodnotenia vylúčili.

Testovanie hypotéz

V tejto časti sa budeme venovať testovaniu hypotéz, či dané podsúbory (1901–1960 a 1947–2006, pre letno-jesennú a pre zimno-jarnú sezónu) denných zrážkových úhrnov pochádzajú z rovnakého rozdelenia. Budeme testovať zmeny v strednej hodnote a v štandardnej odchýlke súborov denných úhrnov zrážok.

Výsledky pre porovnanie strednej hodnoty sú v tabuľke 5. Pre zimno-jarnú, aj pre letno-jesennú sezónu nezamietame na hladine významnosti 0,05 nulovú hypotézu, že obidve obdobia majú rovnakú strednú hodnotu, proti žiadnej z troch alternatívnych hypotéz (nakoľko hladina významnosti α=0,05 v testoch je pre všetky alternatívy menšia ako P-hodnota).

Výsledky pre porovnanie štandardnej odchýlky sú v tabuľke 6. Pre zimno-jarnú sezónu nezamietame na hladine významnosti 0,05 nulovú hypotézu, že obidva súbory majú rovnakú štandardnú odchýlku, proti žiadnej z troch alternatívnych hypotéz. Pre letno-jesennú sezónu túto hypotézu zamietame, pre dve alternatívy.

Hodnotenie periód bez zrážok v trvaní 30 a viac dní a výskyt lesných požiarov v SR

Požiarne nebezpečenstvo vzrastá s výskytom dlhotrvajúcich bezzrážkových období. Pri zhodnotení extrémne suchých periód na stanici Hurbanovo sme nadviazali na výsledky spracované Petrovičom (1960). V rade denných zrážkových úhrnov sme spočítali periódy bez zrážok trvajúce 30 a viac dní za obdobie 1951–2006. Podľa Petroviča a kol. (1960), perióda sucha nie je prerušená, ak v nej spadnú zrážky s denným úhrnom pod 1 mm. V tabuľke 7 sú uvedené dátumy začiatku výskytu obdobia bez zrážok a počet dní bez zrážok. Na obr. 7 sú vykreslené počty period bez zrážok nad 29 dní pre jednotlivé dekády a za posledných 7 rokov 2001–2007. Najdlhšie obdobie bez zrážok v trvaní 83 dní v stanici Hurbanovo sa vyskytlo v roku 1947. Od roku 1951 sa za 10 rokov v priemere vyskytuje 5-6 období bez zrážok v trvaní 30 a viac dní. Je pozoruhodné, že v desaťročí 1901–1910 (v období dlhodobého minima Slnečnej aktivity) sa nevyskytla ani jedna takáto perióda. Suché periódy v trvaní od 50 do 59 dní bez zrážok sa vyskytli 6 krát a od 60 do 90 dní 1 krát za 130 rokov meraní v Hurbanove, t.j približne jedna takáto udalosť za 20 rokov.

Tabuľka 5. Výsledky testovania zmeny strednej hodnoty pre zimno-jarnú a letno-jesennú sezónu. 95,0% interval spoľahlivosti

Table 5. Testing results of change of mean value in the winter-spring and the summer-autumn seasons. 95.0% confidence interval

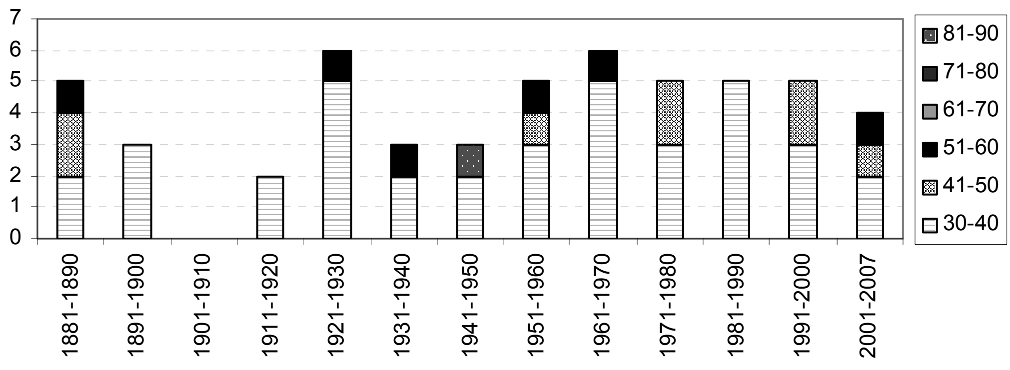
ZRZJ01_60: 3.619 +/- 0.1407 ZRZJ47_06: 3.616 +/- 0.1486	ZRLJ01_60: 5.38373 +/- 0.230675 ZRLJ47_06: 5.43086 +/- 0.247678
Null hypothesis: mean1 = mean2	Null hypothesis: mean1 = mean2
(1) Alt. hypothesis: mean1 NE mean2 assuming eq. variances: t = 0.0330357 P-value = 0.97364 not assuming eq. var.: t = 0.0330314 P-value = 0.973644 (2) Alt. hypothesis: mean1 > mean2 assuming eq. variances: t = 0.0330357 P-value = 0.48682 not assuming eq. var.: t = 0.0330314 P-value = 0.486822 (3) Alt. hypothesis: mean1 < mean2 assuming eq. variances: t = 0.0330357 P-value = 0.51318 not assuming eq. var.: t = 0.0330314 P-value = 0.513178	(1) Alt. hypothesis: mean1 NE mean2 assuming eq. variances: t = -0.27324 P-value = 0.784665 not assuming eq. var.: t = -0.272903 P-value = 0.784924 (2) Alt. hypothesis: mean1 > mean2 assuming eq. variances: t = -0.27324 P-value = 0.607668 not assuming eq. var.: t = -0.272903 P-value = 0.607538 (3) Alt. hypothesis: mean1 < mean2 assuming eq. variances: t = -0.27324 P-value = 0.392332 not assuming eq. var.: t = -0.272903 P-value = 0.392462

Tabuľka 6. Výsledky testovania zmeny štandardnej odchýlky pre zimno-jarnú a letno-jesennú sezónu. 95,0% interval spoľahlivosti
Table 6. Testing results of change of standard deviation in the winter-spring and the summer-autumn seasons. 95.0% confidence interval

ZRZJ01_60: [4.53658;4.73572] ZRZJ47_06: [4.54304;4.75335]	ZRLJ01_60: [6.93445;7.26088] ZRLJ47_06: [7.2212;7.57171]
Null hypothesis: sigma1 = sigma2	Null hypothesis: sigma1 = sigma2
(1) Alt. hypothesis: sigma1 NE sigma2 F = 0.994926 P-value = 0.87261 (2) Alt. hypothesis: sigma1 > sigma2 F = 0.994926 P-value = 0.563695 (3) Alt. hypothesis: sigma1 < sigma2 F = 0.994926 P-value = 0.436305	(1) Alt. hypothesis: sigma1 NE sigma2 F = 0.920898 P-value = **0.0144241 – zamietame nulovú hypotézu** (2) Alt. hypothesis: sigma1 > sigma2 F = 0.920898 P-value = 0.992788 (3) Alt. hypothesis: sigma1 < sigma2 F = 0.920898 P-value = **0.00721205 – zamietame nulovú hypotézu**

Tabuľka 7. Dátumy začiatku výskytu obdobia bez zrážok nad 29 dní a počet dní bez zrážok, stanica Hurbanovo
Table 7. Date of occurrence of periods without precipitation longer than 29 days and number of days without precipitation at Hurbanovo

Dátum začiaku	počet dní	Dátum začiaku	počet dní	Dátum začiaku	počet dní	Dátum začiaku	počet dní
22.XII.1881	58	24-VIII-1926	34	13-IX-1961	35	10-IX-1985	34
8.I.1887	42	24-VIII-1926	34	1-I-1964	31	8-X-1988	36
2.XII.1888	39	28-II-1929	31	30-IX-1965	35	9-I-1989	40
8.II.1889	41	10-VI-1932	30	7-IX-1966	36	1-I-1991	36
28.I.1890	33	3-VIII-1932	50	21-I-1968	35	13-II-1991	34
27.X.1892	36	17-VII-1933	31	29-VIII-1969	57	14-VII-1992	49
18.I.1896	37	***26-VII-1947***	***83***	28-VII-1973	30	5-I-1997	38
1.XII.1897	38	10-II-1949	33	25-III-1975	41	23-I-1998	41
4-II-1913	34	2-III-1950	32	9-III-1976	44	5-II-2003	59
22-X-1920	30	6-IV-1952	30	23-X-1978	35	14-X-2005	34
8-III-1921	38	5-III-1953	35	6-V-1979	32	20-IX-2006	34
19-IX-1921	34	7-XI-1953	50	27-III-1981	31	17-XII-2006	43
5-XII-1924	56	10-I-1959	42	18-X-1983	39		

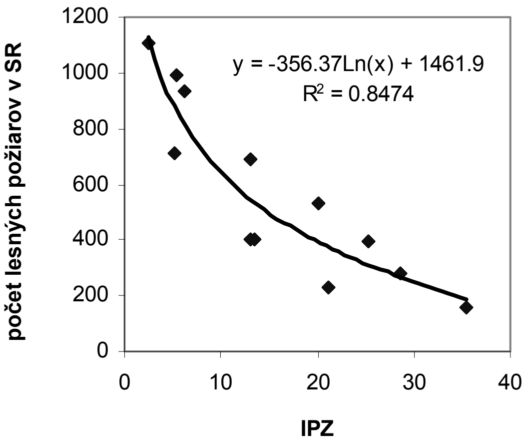


Obr. 7. Počty periód bez zrážok v trvaní 30 a viac dní pre jednotlivé desaťročia a za posledných 7 rokov 2001–2007 v stanici Hurbanovo.
Fig. 7. Number of periods without precipitation longer than 30 days in individual decades, and in last 7 years at Hurbanovo.

Zvýšený výskyt lesných požiarov a požiarov v poľnohospodárstve tesne kopíruje výskyt suchých období. Extrémne dlhé bezzrážkové obdobia – predovšetkým v jarných a letných mesiacoch – majú priamy vplyv na zvýšenie počtu lesných požiarov. Na obr. 8 je vykreslená závislosť počtu lesných požiarov v danom roku na minime indexu predchádzajúcich zrážok (IPZ) za mesiace apríl–máj (1992–2004). Index predchádzajúcich zrážok v tejto práci bol počítaný z denných zrážkových úhrnov na stanici Hurbanovo podľa vzťahu:

$$IPZ = \sum_{i=1}^{30} P_{-i}.k^{i} \qquad (1)$$

kde
IPZ – index predchádzajúcich zrážok za 30-predchádzajúcich dní,
P_{-i} – denný zrážkový úhrn v dni –i,
K – empirický koeficient, k=0,87.



Obr. 8. Závislosť medzi minimom indexu predchádzajúcich zrážok za mesiace apríl a máj v Hurbanove a počtom lesných požiarov v roku na Slovensku podľa štatistických ročeniek, obdobie 1992–2004.
Fig. 8. Relationship between minimal indecees of antecedent precipitation (IPZ) in April-May period at Hurbanovo and number of annual forest fires in Slovakia according to Statistical Yearbooks, period 1992–2004.

Z tohoto vyplýva, že stanica Hurbanovo je vhodná stanica na vyjadrenie požiarneho nebezpečenstva pre územie SR. Bolo by potrebné dané vzťahy vypočítať pre menšie územné celky (Parajka a kol., 2003; Szolgay a kol., 2007) a pre viaceré zrážkomerné stanice, ale takúto štatistiku požiarovosti nemáme k dispozícii. Taktiež nie je možné spracovať dlhšie obdobie, nakoľko pred rokom 1990 bola pri vykazovaní požiarovosti používaná iná metodika.

Závery

Z vizuálneho porovnania grafov na obr. 4-5 vyplýva, že v období 1947–2006 došlo k zníženiu počtu zrážkových udalostí od 0,8 do 12,8 mm. Počet vysokých denných zrážkových úhrnov sa nezmenil v zimno-jarnom období. V letno-jesennom období v poslednom tridsaťročí sa vyskytlo viac denných zrážkových úhrnov v intervale od 25,6 po 51,2 mm. Štatisticky nebol preukázaný nárast počtu maximálnych zrážkových udalostí nad 51,2 mm. Z výsledkov testovania hypotéz vyplýva, že pre zimno-jarnú, aj pre letno-jesennú sezónu nezamietame na hladine významnosti 0,05 hypotézu, že obidve 60-ročné obdobia majú rovnakú strednú hodnotu. V letno-jesennnej sezóne mohlo dôjsť k zväčšeniu štandardnej odchýlky v dôsledku menšieho výskytu zrážkových úhrnov zo stredu intervalu. Je na škodu tejto práce, že sme nemali k dispozícii denné úhrny zrážok z Hurbanova už od roku 1875, teda za celé pozorované obdobie. V období 1875–1900 sa totižto vyskytli dve zrážkové udalosti s denným úhrnom nad 75 mm (1875 - 82,5mm, v roku 1893 -75,5mm) (Gaál a Lapin, 2002) a v roku 1900 bol dosiahnutý historicky najvyšší ročný zrážkový úhrn. Toto obdobie by malo byť zahrnuté do štatistického spracovania.
Najdlhšie obdobie bez zrážok v trvaní 83 dní v stanici Hurbanovo sa vyskytlo v roku 1947. Od roku 1951 sa za 10 rokov v priemere vyskytuje 5-6 období bez zrážok v trvaní 30 a viac dní. V desaťročí 1901–1910 sa nevyskytla ani jedna takáto perióda. Suché periódy v trvaní nad 50 a viac dní bez zrážok sa vyskytli 7 krát za 130 rokov meraní v Hurbanove, t.j. približne jedna takáto udalosť za 20 rokov.
Dôkladnej štatistickej analýze meraných radov denných úhrnov zrážok je potrebné venovať naďalej pozornosť. Bolo by potrebné štatisticky vyhodnotiť denné údaje zo všetkých staníc v SR s pozorovaniami od roku 1871 (Košice, Oravská Lesná a Hurbanovo) aj od roku 1901. Taktiež by bolo potrebné vyhodnotiť údaje zo staníc z ešte dlhšími pozorovaniami zo staníc v strednej Európe, napr. zo stanice Viedeň, Praha: Klementinum, Mníchov, Bazilej, Innsbruck a pod. Je potrebné identifikovať dlhodobé cyklické zložky a analyzovať ich telekonekciu so slnečnou aktivitou. Samozrejme, bolo by potrebné spracovať aj zrážkové udalosti v kratšom časovom kroku než je jeden deň zo staníc s ombrogrammi (Zhang, 2008).
Teóriu o raste extremality zrážkových úhrnov je potrebné podložiť konkrétnymi analýzami meraných údajov z viacerých staníc. Na stanici Hurbanovo tridsaťročie 1961–1990 nie je z dlhodobého pohľadu vhodné na kalibráciu klimatických modelov (pozri obr. 7b v prvej časti štúdie). Po suchej perióde dvoch desaťročí 1971–1990 sa nám môže javiť obdobie 1991–2005 ako mimoriadne extrémne. Nemôžeme vylúčiť, že také obdobie, aké prežívame dnes, sa na stanici Hurbanovo v minulosti už vyskytlo.

Poďakovanie

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Literatúra

Bulletin 17b (1982): Flood flow Frequency. US Geological Survey, Virginia, 194.

Gaál, L., Lapin, M. (2002): Extreme several day precipitation totals at the Hurbanovo observatory (Slovakia) during the 20th century. Contr. to Geophysics and Geodesy, Vol. 32, No. 3, 2002, 197-213.

Gaál, L., Lapin, M., Szolgay, J. (2005): Regional frequency analysis of k-day precipitation totals in the Slovak Republic – delineation of homogeneous groups. Geophysical Research Abstracts, Vol. 7, SRef-ID: 1607-7962/gra/EGU05-A-03408, EGU 2005,.

Lapin M., Faško, P. (1998): Denné úhrny zrážok v Hurbanove v období 1871–1995. Bulletin SMS pri SAV. 9, 1, 13-20.

Lapin, M. (2004): Detection of changes in the regime of selected climatological elements at Hurbanovo. Contributions to Geophys. and Geodesy. 34/2, 169-193.

Lapin, M., Damborská, I., Gaál, L., Melo, M. (2003): Possible precipitation regime change in Slovakia due to air pressure and circulation changes in the Euro-Atlantic area until 2100. Contributions to Geophysics and Geodesy, 33/ 3, 161-190.

Lapin, M., Damborská, I., Melo, M. (2001): Downscaling of GCM outputs for precipitation time series in Slovakia. Meteorologický časopis. IV, 3, 29-40.

Lapin, M., Damborská I., 2007: Methods of extreme weather events selection and some results of elaboration. Int. Conf.: Bioclimatology and natural hazards. Sept. 2007, 14.

Melo, M. (2003): Klimatické modely a ich využitie na odhad klimatických zmien na území Slovenska. Diz. práca GfÚ SAV, Bratislava, 155.

Parajka, J., Mészároš, I., Szolgay. J. (2003): Určovanie plošného rozdelenia úhrnov zrážok pre modelovanie odtoku s využitím metód GIS. Acta Hydrologica Slovaca, 4, 1, 165-175.

Petrovič, Š. a kol. (1960): Klimatické pomery Hurbanova. HMÚ, Praha, 138-161.

Procházka, M., Deyl, M., Novický, O., 2001: Technology for detecting trends and changes in time series of hydrological and meteorological variables. Change and Trend Problem Analysis – CTPA. CD ROM, CHMI, WMO, Praha, 25.

Smakhtin, V.U., Hughes, D.A. (2007): Automated estimation and analyses of meteorological drought characteristics from monthly rainfall data. Environmental Modelling & Software, 22/6, 880-890.

Stehlová, K., Kohnová, S., Szolgay., J. (2001): Analýza maximálnych dvojdňových úhrnov zrážok v oblasti horného Hrona. Acta Hydrologica Slovaca, 2, 2, 167-174.

Szolgay, J., Parajka, J., Kohnová, S., Hlavčová, K., Lapin, M., Faško, P., 2007: Testing of mapping approaches for estimation of 100-year maximum daily precipitation totals in the upper Hron River basin. Contributions to Geophysics and Geodesy, 37, 3, 225-246.

Šamaj, F., Valovič, Š., Brázdil, R. (1985): Denné úhrny zrážok s mimoriadnou výdatnosťou v ČSSR v období 1901–1980. Zborník prác SHMÚ, 24. Alfa, Bratislava. 9-113.

Štepánek, P. (2003): AnClim - software for time series analysis. Dept. of Geography, Fac. of Natural Sciences, MU, Brno; http://www.sci.muni.cz/~pest/AnClim.html.

Zhang, Q., Yu Xu, Ch., Zhang, Z., Chen, Y., D., Liu, Ch., Lin, H.(2008): Spatial and temporal variability of precipitation maxima during 1960–2005 in the Yangtze River basin and possible association with large-scale circulation. J. of Hydrol., 353, 215-227.

ANALYSIS OF THE STATISTICAL CHARACTERISTICS OF DAILY PRECIPITATION AT HURBANOVO IN DIFFERENT PERIODS: PART II. FREQUENCY ANALYSIS

Meteorological observatory Hurbanovo (former Ógyalla) is a representative station for the region of the Danube lowland (Petrovič et al, 1960). The daily precipitation series is processed since 1872 and it was analysed in many studies in last years (see Šamaj et al, 1985; Melo, 2003; Gaál and Lapin, 2002; Gaál et al, 2005; Lapin 2004; Lapin and Faško, 1998; Lapin et al, 2001, 2003; Lapin and Damborská, 2007).
The aim of this part of the study was the frequency analysis (analysis of histograms, empirical distribution curves and frequency curves) of daily precipitation depths in different periods. The statistical processing was done using software packages EXCEL, STAGRAPHICS, CTPA, AnClim and BestFit (Štepánek, 2003, Procházka et al, 2001).

The visual comparison of the Figs. 4-5 shows that the number of precipitation events between 0.8 and 25.6 mm decreased in 1947–2006. Number of events with high precipitation did not change in the winter-spring period. Number of events in the interval between 25.6 to 51.2 mm increased. The increase of number of events over 51.2 mm was not found. Then we tested the hypotheses whether subsets (1901–1960 and 1947–2006, during the winter-spring, and the summer-autumn seasons) of daily precipitation have the same distribution. We tested changes in mean value and in standard deviation. Testing results of change in mean value are in Table 5. We cannot reject the zero hypothesis on 0.05 confidence level that both periods have the same mean value for any of both seasons.

Testing results of change in standard deviation are in Table 6. In the winter-spring season we do not reject the zero hypothesis on 0.05 confidence level that both periods have the same standard deviation. In the summer-autumn season this hypothesis is rejected.

The last aim of the study was the assessment of periods without precipitation longer than 29 days. In evaluation of extreme dry periods we resumed the analysis done by Petrovič et al. (1960). We calculated the periods of days without precipitation longer than 29 days in the series of daily precipitation in 1951–2006. Date of occurrence of periods without precipitation longer than 29 days and number of days without precipitation at Hurbanovo can be found in Table 7. Number of periods without precipitation longer than 29 days in individual decades, and in last 7 years at Hurbanovo are presented Fig. 7. The longest period of days without precipitation was 83 days in 1947. The periods without precipitation longer than 29 days occur usually 5-6 times in each decade. Dry periods longer than 50 days occurred 7 times during the 130 years observation. Long dry periods during the summer period are very dangerous because of forest fires occurrence. The increased number of forest and field fires correlates very closely with occurrence of the dry periods. The relation between minimal indexes of antecedent precipitation (IPZ) in April-May period and number of annual forest fires in Slovakia according to Statistical Yearbooks in the period 1992–2004 Is in Fig. 8. The index of antecedent precipitation was calculated according to (1), where P is daily precipitation depth, and k is empirical coefficient.

Conclusion

A firm statistical analysis of measured daily precipitation series is very important. All Slovak stations with observations since 1871 (Košice, Oravská Lesná and Hurbanovo) as well as stations with data since 1901 should be processed. Also the comparison with other stations with long data series in Central Europe is needed. It is important to identify the long-term cyclic component and separate them from trend changes due to air temperature increase.

The theory of increase of precipitation extremality has to be supported by concrete analyses of measured data series from different stations. The usual 30-years period 1961–1990 is not suitable from the long-term point of view for calibration of the climatic models. After the dry period of two decades 1971–1990 we can consider the period 1991–2005 as very extreme one. It means that the same precipitation conditions we experience today were observed in the past in Hurbanovo, and possibly in wider region, as well.

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RISKS DUE TO VARIABILITY OF K-DAY EXTREME PRECIPITATION TOTALS AND OTHER K-DAY EXTREME EVENTS

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Several alternative definitions of extreme events are proposed. As the first step a statistical analysis of daily precipitation measurement time series from the Hurbanovo SHMI Observatory and elaboration of potentially dangerous precipitation events is carried out. Then, combined characteristics based on daily temperature, daily air humidity and daily precipitation totals are computed. The drought index based on normalized deviations from long-term averages is defined. Alternatively, to define extreme events "Data envelopment analysis" (DEA) is employed with K-day periods of values of temperature, humidity and precipitation corresponding to decision making units. The results of all definitions of extreme events are compared.

KEY WORDS: extreme events, precipitation, humidity, temperature, drought index, DEA analysis

Pavol Brunovský, Milan Lapin, Igor Melicherčík, Ján Somorčík, Daniel Ševčovič: RIZIKÁ SPÔSOBENÉ VARIABILITOU K-DENNÝCH EXTRÉMNYCH ÚHRNOV ZRÁŽOK A INÝMI EXTRÉMNYMI UDALOSŤAMI

V článku navrhujeme niekoľko definícií extrémnych udalostí. Ako prvý krok je spravená štatistická analýza denných úhrnov zrážok z observatória SHMÚ v Hurbanove na základe ktorej označujeme extrémne udalosti. Následne počítame kombinované charakteristiky založené na denných údajoch teploty, vlhkosti vzduchu a denných úhrnoch zrážok. Index sucha je založený na normalizovaných odchýlkach od dlhodobých priemerov. Alternatívne definujeme extrémne udalosti na základe DEA analýzy, kde K-denné periódy teploty, vlhkosti a zrážok slúžia ako rozhodovacie jednotky. Výsledky všetkých prístupov nakoniec porovnáme.

KĽÚČOVÉ SLOVÁ: extrémne udalosti, atmosférické zrážky, vlhkosť, teplota, index sucha, DEA analýza

Introduction

It is commonly accepted that one of the features of the climatic changes in the past is an increasing number of extreme weather events of various kind - draughts, floods, windstorms, etc. But what is an extreme event? For instance, drought cannot be naturally characterized by a single quantity. Rather, it is a combination of high temperature, low humidity low precipitation and possibly other quantities like duration.

A common tool for the definition of an extreme event is a drought index (Klementová, Lintschman (2001)) incorporating several kinds of data. The disadvantage of this method is that it involves subjective components, e.g. the choice of weights of the data and the choice of the threshold.

In this paper we introduce a completely new methodology of the identification of extreme events, the Data Envelopment Analysis (DEA) and compare its results with the results of the index approach. DEA has been widely used in the evaluation in the field of operations research as a tool for the evaluation of "decision making units". To our knowledge this is the first application of DEA for the definition of extreme events.

Extreme precipitation totals

We studied the time series of daily precipitation totals at Hurbanovo from 1901 to 2006. Initially we computed yearly averages of daily precipitation totals (Fig. 1). They are denoted by dots and triangles. Dots stand for yearly averages of precipitation totals over rainy days (with precipitation total > 0.0 mm) of particular years. Of course, the dots lie above the triangles. The U-shape of the solid line suggests that daily precipitation totals of rainy days during the beginning of the 20th century as well as during several last years were higher than in the middle of the previous century. The difference of the solid and dashed line is depicted in Fig. 2. Here the U-shape is even more visible. Since the yearly precipitation totals seem to be a stationary series (dashed line in Fig. 1) this means that the number of rainy days at the beginning of the past century and in the last years was lower than in between whereas rainfalls were heavier. Influence of some worse observation quality at low precipitation totals before 1920 is possible.

The above formulated conjecture about the trend of the number of rainy days based on Fig. 1 and 2 corresponds perfectly with Fig. 3 showing the number of rainy days.

Further, we studied the occurrence of extreme rainfalls. For the one-day precipitation totals the limits were set to 40 mm, 50 mm, 60 mm and 70 mm. These limits were exceeded 38-, 10-, 3- and 3-times respectively. The distribution of these extreme events in the period from 1901 to 2006 can be seen in Fig. 4. We note that the highest one-day precipitation total was 88.8 mm on August 20, 1918.

The study was extended to two- and three-day precipitations totals (see Fig. 5 and 6). The limits were set to 50 mm, 60 mm, 70mm and 80 mm in case of two-day precipitation totals (exceeded 37-, 14-, 4-, and 3-times respectively) and to 60 mm, 70 mm, 80mm and 90 mm in case of three-day precipitation totals (exceeded 31-, 11-, 5-, and 2-times respectively).

Fig. 4, 5 and 6 suggest that the distribution of the heavy rainfalls in the period from 1901 to 2006 is quite uniform.

The effect of a heavy rainfall can become really serious when it continues to rain in the following days. This motivated us to look at the average number of rainy days after one- two- or three-days with precipitation totals over 40 mm, 50 mm or 60 mm respectively (the average is taken through all extreme events in a particular year). The results are in Fig. 7, 8 and 9. No increasing or decreasing trend can be seen there.

Drought index

To begin we investigated the occurrence of series of K days with very low precipitation totals. We searched for series of at least 5 no-rain days, series of at least 15 days with precipitation totals below 1 mm and series of at least 30 days with precipitation totals below 5 mm. Their occurrence is shown in Fig. 10, 11 and 12.

Note the U-shape in Figure 10 which is probably due to the lower number of rainy days at the beginning of the last century and in the last years (see Fig. 3). On the other hand, Fig. 11 and 12 do not show any deviation from the stationary trend: the occurrence of longer drought periods does not seem to have changed over the last century.

As a second step we have calculated the combined characteristics based on daily temperature, daily air humidity and daily precipitation. The drought index for the K-day period (in our calculations K=10 successive days) i in the j-th year is defined as follows:

$$D_{ij} = w_t \frac{t_{ij} - \overline{t}}{\sigma_t} - w_p \frac{p_{ij} - \overline{p}}{\sigma_p} - w_h \frac{h_{ij} - \overline{h}}{\sigma_h}, \qquad (1)$$

where

t_i, p_i, h_i are average values of temperature, precipitation and humidity respectively in the period i,

$\overline{t}$, $\overline{p}$, $\overline{h}$ are long term (period 1951-2005) averages of the temperature, precipitation and humidity respectively,

σ_t, σ_p, σ_h are standard deviations (period 1951-2005) of the temperature, precipitation and humidity respectively,

w_t, w_p, w_h are the weights of the temperature, precipitation and humidity factors fulfilling $w_t + w_p + w_h = 1$.

The definition of the drought index is similar to Klementová, Lintschman (2001) where only temperature and precipitation was taken into account. Furthermore, they used the entire growing season as a period. In our calculations we have used the weights for the factors of temperature, precipitation and humidity

$$w_t = w_p = w_h = 1/3.$$

Hereafter we identify the K=10-day period with the beginning of the period. The day is supposed to be a drought, if the drought index of the corresponding period is higher than 95% sample quantile of calculated indices (see Fig. 13).

The number of drought days in corresponding years can be seen in Fig. 14 (left). One can observe that this number is slightly increasing. The monthly distribution of the drought days could be seen in Fig. 14 (right). The month with the highest number of drought days is August.

Since for agriculture the growing season is more important than the rest of the year we performed the same study as above but the precipitation, temperature and humidity data were only from April to the end of September. One can observe from Fig. 15 that they are very similar to the situation when the whole-year data were taken into account.

Recall the standardization (1). Another approach to the standardization of the data from the i-th period in the j-th year is to use long-term averages and standard deviation estimates appertaining to the i-th period. The drought index will be defined as

$$D_{ij} = w_t \frac{t_{ij} - \overline{t}_i}{\sigma_{t_i}} - w_p \frac{p_{ij} - \overline{p}_i}{\sigma_{p_i}} - w_h \frac{h_{ij} - \overline{h}_i}{\sigma_{h_i}}. \quad (2)$$

We consider this approach as more natural because it compares weather parameters with the averages for that particular period. Hence, the period is considered as extreme when it differs from the long-term averages for that particular period, not from the long-term averages of the weather parameters of all periods.

We tested our approach on the growing season data. The results of year comparisons are depicted in Fig. 16 (left) and are quite similar to those in Fig. 14 (left) and 15 (left). However, the monthly distribution has changed: as one can see in Fig. 16 (right) also in May and June drought periods occur quite frequently (cf. Fig. 14 (right) and 15 (right)).

Extreme events defined using the DEA methodology

Data Envelopment Analysis (DEA) has its origin in Operations Research. It is a tool for the evaluation of "decision making units" (DMUs) the efficiency of which is measured by several parameters rather than a single quantity. Its basic aim is to single out *efficient* DMUs. Those are DMUs that lie on the *efficient frontier*. This is, by definition, a part of the boundary of the (smallest convex) region filled by the parameter vectors of all the DMUs.

In our case DMUs correspond to periods of days of a fixed length (K=10 days), the parameters being meteorological data strings (precipitation, temperature, humidity) for the particular periods. Extreme weather periods then correspond to efficient DMUs.

Of course, DMUs as well as weather data strings can be evaluated alternatively by a single index representing a weighted sum of the parameters with chosen fixed weights (as in previous section). Efficient DMUs, or extreme weather events, can then be declared as those the index of which exceeds a fixed threshold. Both the weights and the threshold have to be chosen subjectively.

The advantage of DEA is that the specification of efficient DMUs (or, in our case, extreme weather events) is free of any subjective component. In a certain sense it can be viewed as an evaluation by a weighted sum that is automatically chosen as the most beneficial for each of the DMUs/events individually, but not decreasing benefits of others. In addition, the efficient frontier identifying the extreme events is determined structurally without the need of a choice of any threshold.

Computation of the efficient units is involved when applying DEA methodology. There are several computation methods for DEA, all of them based on linear programming algorithms. We have employed the weighted "additive model" method used in Ševčovič et al. (2001). For a comprehensive general treatment of the DEA method the reader is referred to Cooper *et al.* (2000).

Dry and hot extreme periods

In accord with the previous section we define the extreme period as a period with high temperature, low precipitation and low humidity.

The number of drought days in corresponding years can be seen in Fig. 17 (left). One can observe that this number is slightly increasing. The monthly distribution of the drought days could be seen in Fig. 17 (right). The months with the highest number of drought days are July and August.

Conclusions

We have studied several methodologies of defining extreme events. The methodologies have been compared using the time series of daily precipitation, humidity and temperature at Hurbanovo from 1901 to 2006. First we have calculated the yearly averages of daily precipitation totals. These averages seem to be stationary. Comparing to the averages in the rainy days only, one can conclude that at the beginning and at the end of the last century the number of the rainy days was lower and the rainfalls were heavier. Further we have studied the occurrence of 1-3 days extreme rainfalls. The distribution of heavy rainfalls in the period from 1901 to 2006 is quite uniform.

As a second step we have considered the drought index that combines characteristics based on daily temperature, air humidity and precipitation. The number of drought days seems to be increasing.

Finally, we have used the DEA methodology for definition of extreme events. To our knowledge this is the first application of the DEA method to the determination of extreme events of any kind rather than efficiency of performance. Unlike the index method, method is not subject to subjective choices of weights and threshold but is more computationally involved. The DEA results confirm the ones obtained by the drought index: The number of extreme drought periods is increasing over years, their highest occurrence being in July and August. Continuation of this study may contribute to science of disasters (Bunde et al. 2002).

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List of symbols

D_{ij} - drought index for period *i* and year *j*

$\overline{h}$ - long term average of humidity

h_{ij} - average value of humidity (period *i,* year *j*)

$\overline{p}$ - long term average of precipitation totals

p_{ij} - average value of precipitation totals (period *i,* year *j*)

$\overline{t}$ - long term average of temperature

t_{ij} - average value of temperature (period *i,* year *j*)

σ_h - standard deviation of humidity

σ_p - standard deviation of precipitation totals

σ_t - standard deviation of temperature

w_h - weight of the humidity factor

w_p - weight of the precipitation totals factor

w_t - weight of the temperature factor

REFERENCES

BUNDE A., KROPP J., SCHELLNHUBER H. J. (Eds.), 2002: The Science of Disasters (Climate Disruptions, Heart Attacks, and Market Crashes). Springer Verlag Berlin Heidelberg, 453 pp.

COOPER W. W., SEIFORD L. M., TONE K., 2000: Data Envelopment Analysis (a comprehensive text with models, applications, references and DEA-solver software). Kluwer Academic Publishers, Boston 2000.

KLEMENTOVÁ E., LITSCHMAN T., 2001: Výsledky hodnotenia sucha v oblasti Hurbanova. Sucho, hodnocení a predikce. Pracovní seminář, ČHMÚ, Brno 19.11.2001.

LAPIN M., FAŠKO P., 1997: Inter-sequential variability of atmospheric precipitation totals in Slovakia. Acta Meteorologica Universitatis Comenianae, XXVI, 33-74.

ŠEVČOVIČ D., HALICKÁ M., BRUNOVSKÝ P., 2001: DEA analysis for a large structured bank branch network, Central European Journal of Operational Research, 9, 329-342.

RIZIKÁ SPÔSOBENÉ VARIABILITOU K-DENNÝCH EXTRÉMNYCH ÚHRNOV ZRÁŽOK A INÝMI EXTRÉMNYMI UDALOSŤAMI

Pavol Brunovský, Milan Lapin, Igor Melicherčík, Ján Somorčík, Daniel Ševčovič

Mimoriadne počasie, ako zhoda okolností viacerých meteorologických prvkov, máva často rad nepriaznivých dôsledkov na socio-ekonomické systémy. Nezriedka môže takéto počasie iniciovať výsledok charakterizovaný ako prírodná katastrofa. V článku navrhujeme niekoľko definícií extrémnych udalostí. Ako prvý krok je spravená štatistická analýza denných úhrnov zrážok z observatória SHMÚ v Hurbanove na základe ktorej označujeme extrémne udalosti. Je potrebné zdôrazniť, že pozorovania z Hurbanova sú na tento účel zvlášť vhodné kvôli ich overenej dlhodobej spoľahlivosti a časovej homogenite. Následne počítame kombinované charakteristiky založené na denných údajoch teploty vzduchu, vlhkosti vzduchu a denných úhrnoch zrážok. Index sucha je založený na normalizovaných odchýlkach od dlhodobých priemerov. Takto je zabezpečený výpočet indexu sucha iba málo ovplyvnený ročným chodom. Alternatívne definujeme extrémne udalosti na základe DEA analýzy, kde K-denné periódy teploty, vlhkosti a zrážok slúžia ako rozhodovacie jednotky. Výsledky všetkých prístupov nakoniec porovnáme. Metodika spracovania a aj prezentované výsledky predstavujú otvorený systém, ktorý bude možné priebežne doplĺňať, rozširovať a spresňovať.

Zoznam použitých symbolov

D_{ij} - index sucha pre periódu *i* a rok *j*

$\overline{h}$ - dlhodobý priemer vlhkosti

h_{ij} - priemerná vlhkosť (perióda *i,* rok *j*)

$\overline{p}$ - dlhodobý priemer úhrnov zrážok

p_{ij} - priemer úhrnov zrážok (perióda *i,* rok *j*)

$\overline{t}$ - dlhodobý priemer teploty

t_{ij} - priemerná teplota (perióda *i,* rok *j*)

σ_h - smerodajná odchýlka vlhkosti

σ_p - smerodajná odchýlka úhrnov zrážok

σ_t - smerodajná odchýlka teploty

w_h - váha faktora vlhkosti

w_p - váha faktora úhrnov zrážok

w_t - váha faktora teploty

Fig. 1. Average one-day precipitation totals during rainy days and during all days.
Obr. 1. Priemerné jednodňové úhrny zrážok počas zrážkových a všetkých dní.

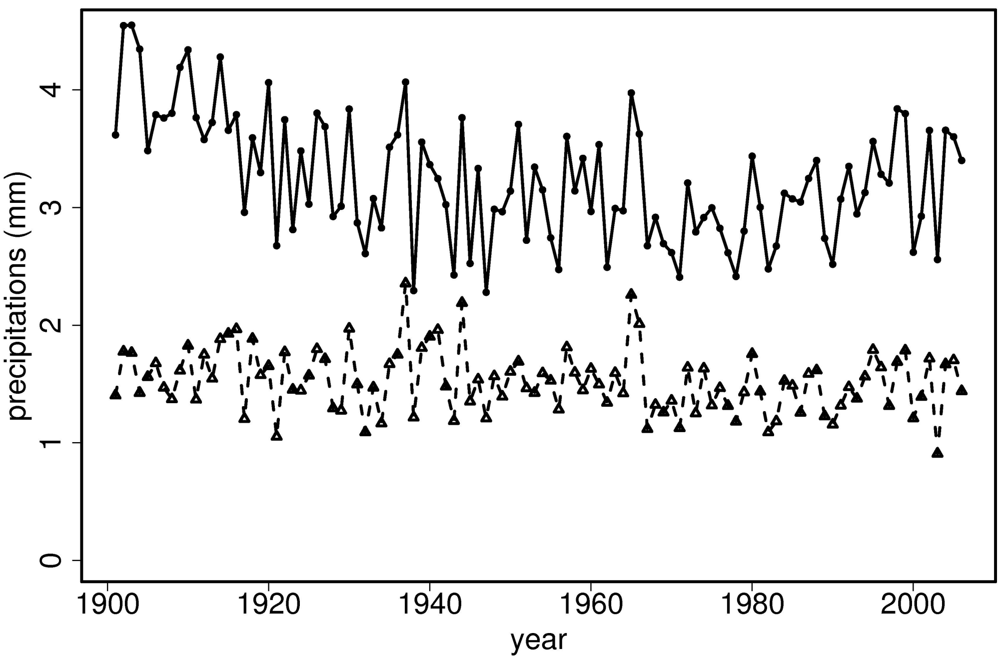


Fig. 2. Difference between average one-day precipitation totals during rainy days and during all days.
Obr. 2. Rozdiel medzi priemernými jednodňovými úhrnmi zrážok počas zrážkových a všetkých dní.

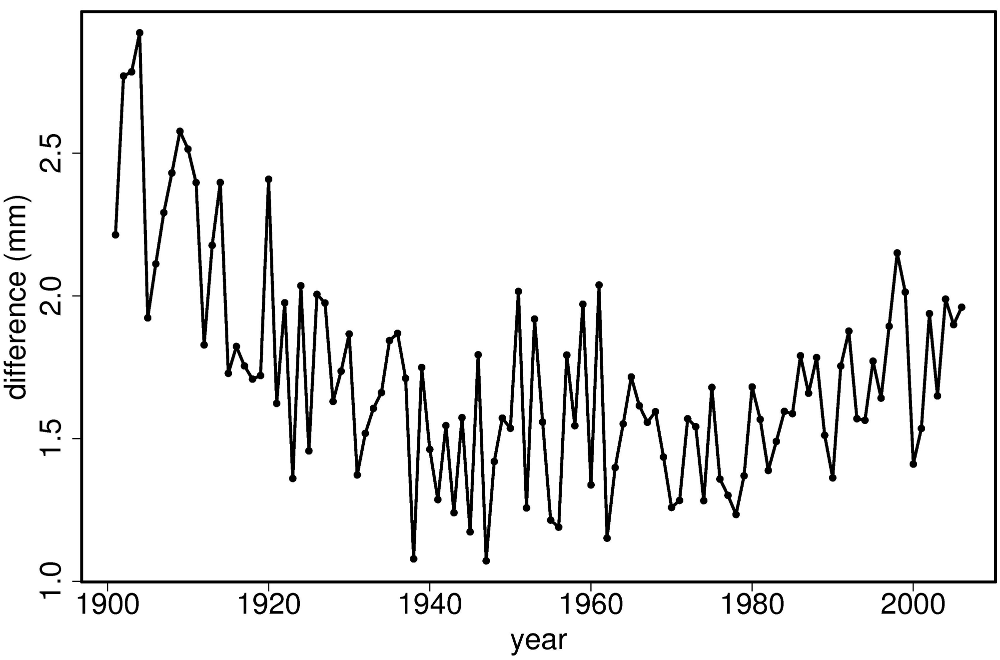


Fig. 3. Number of rainy days.
Obr. 3. Počet zrážkových dní.

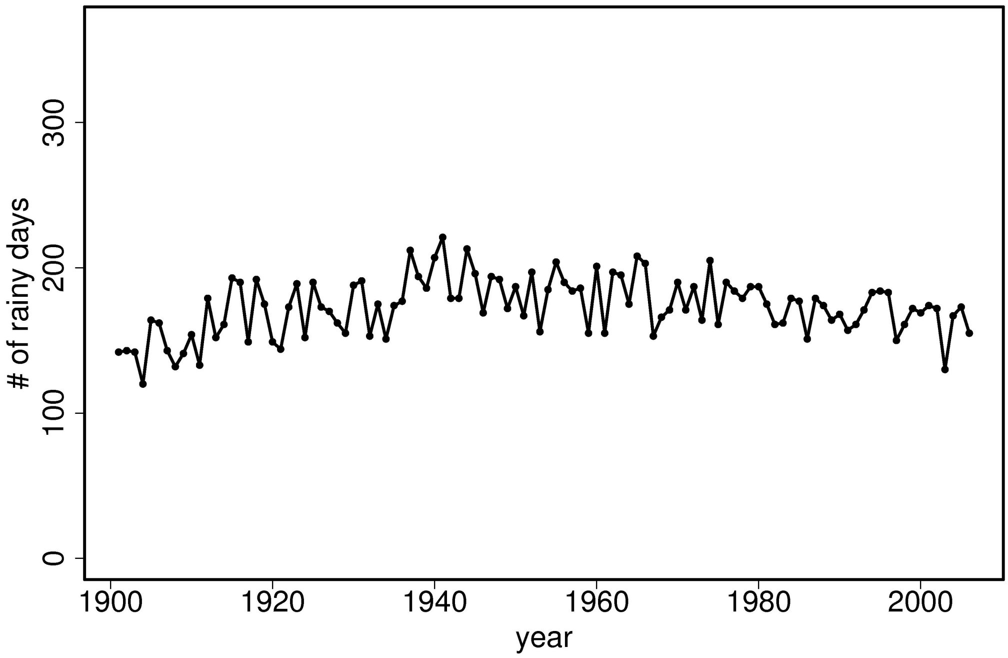


Fig. 4. Number of one-day precipitation totals exceeding a given level of milimeters.
Obr. 4. Počet jednodňových úhrnov zrážok presahujúcich danú úroveň milimetrov.

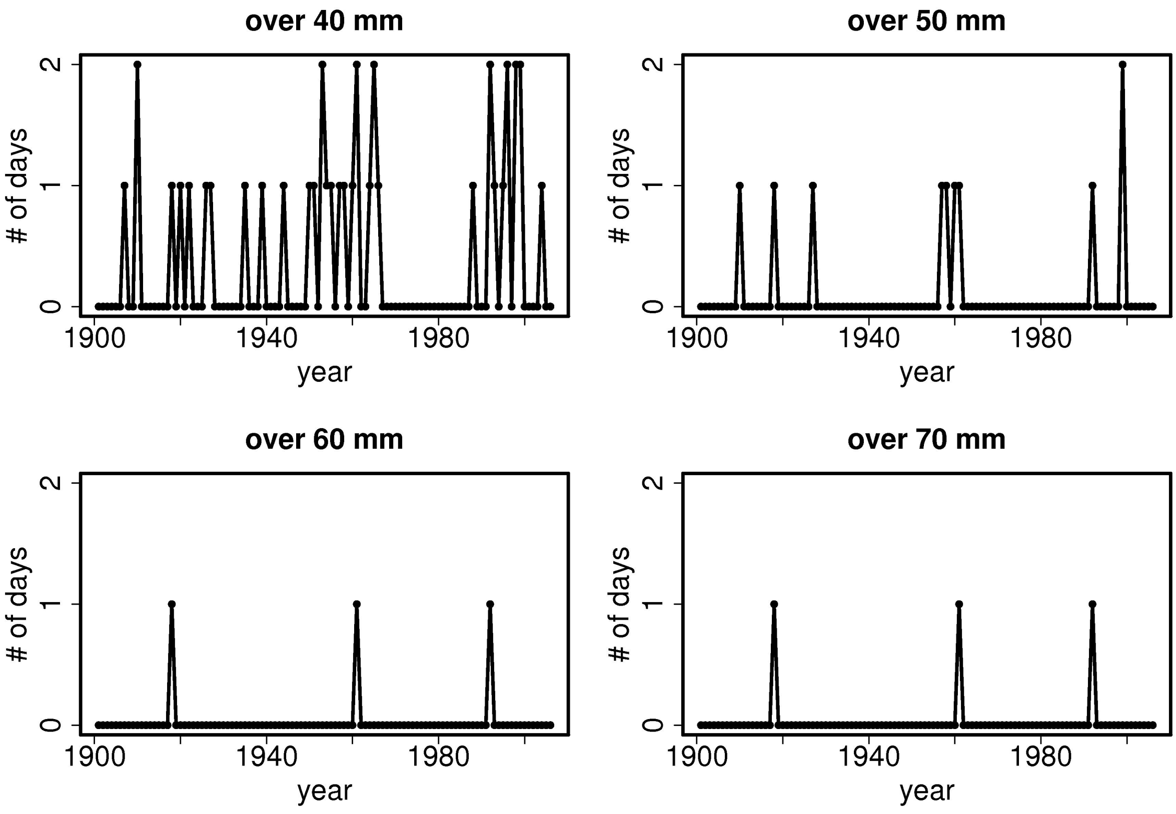


Fig. 5. Number of two-day precipitation totals exceeding a given level of milimeters.
Obr. 5. Počet dvojdňových úhrnov zrážok presahujúcich danú úroveň milimetrov.

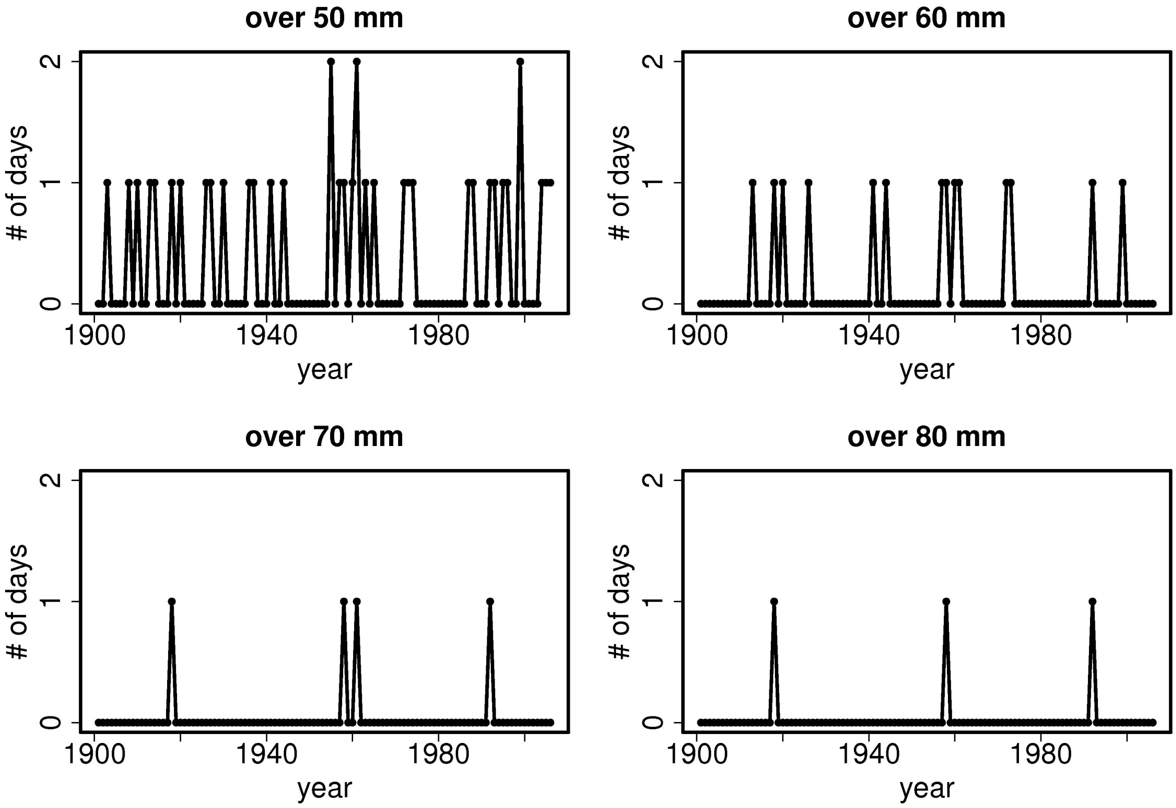


Fig. 6. Number of three-day precipitation totals over exceeding a given level of milimeters.
Obr. 6. Počet trojdňových úhrnov zrážok presahujúcich danú úroveň milimetrov.

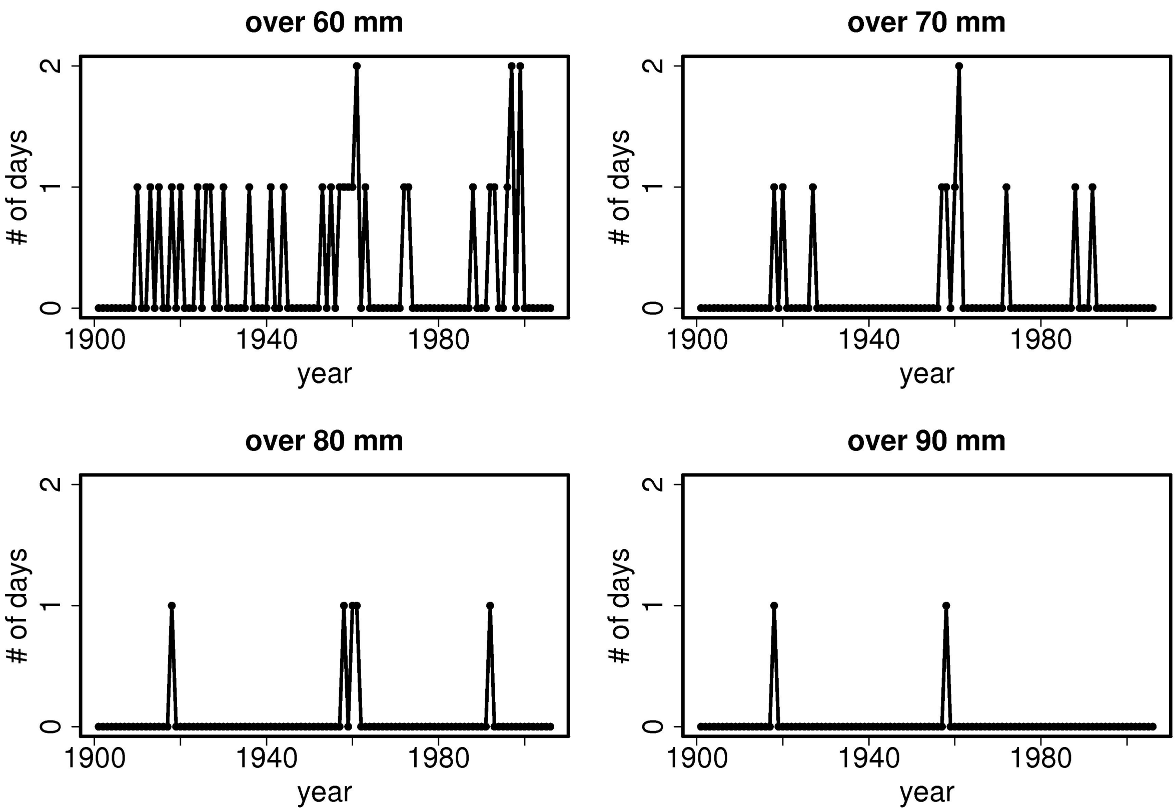


Fig. 7. Average number of rainy days after one-day precipitation totals over 40 mm.
Obr. 7. Priemerný počet zrážkových dní po jednodňových úhrnoch zrážok viac ako 40 mm.

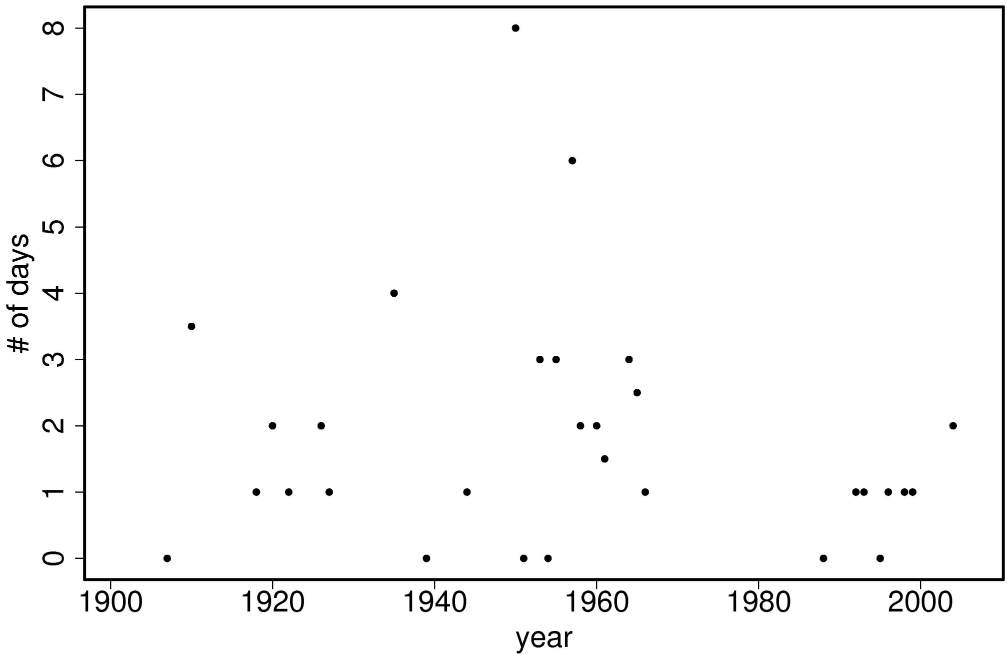


Fig. 8. Average number of rainy days after two-day precipitation totals over 50 mm.
Obr. 8. Priemerný počet zrážkových dní po dvojdňových úhrnoch zrážok viac ako 50 mm.

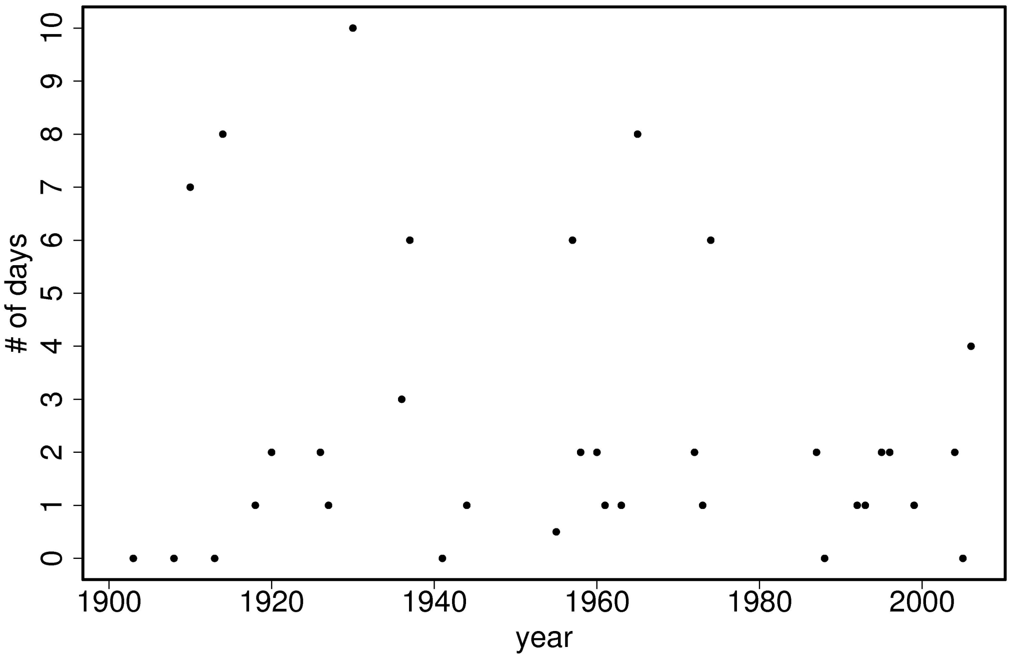


Fig. 9. Average number of rainy days after three-day precipitation totals over 60 mm.
Obr. 9. Priemerný počet zrážkových dní po trojdňových úhrnoch zrážok viac ako 60 mm.

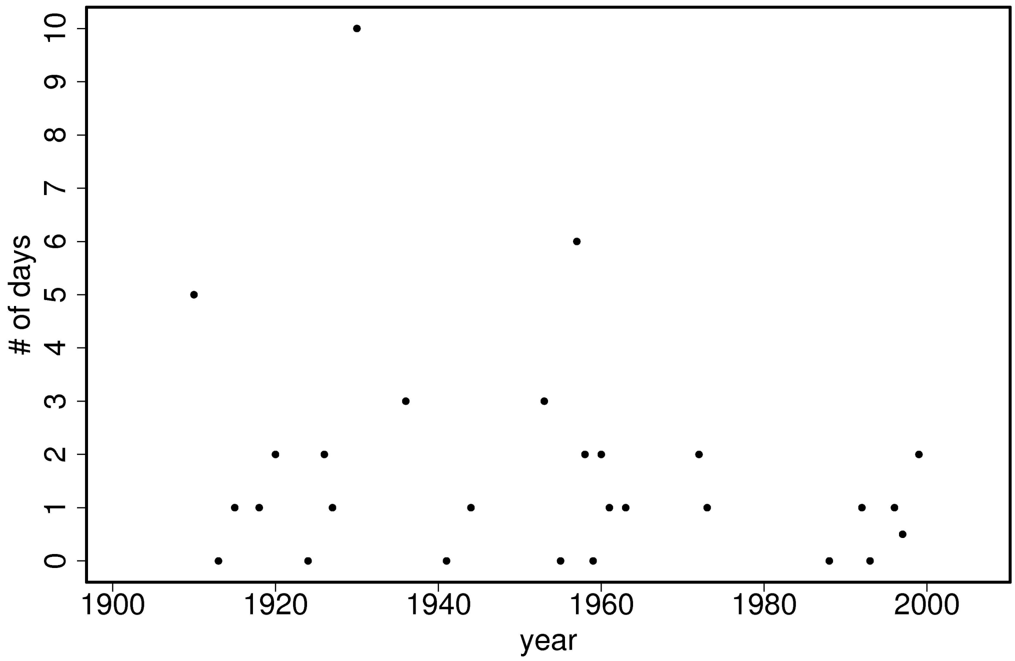


Fig. 10. Number of series of at least 5 no-rain days.
Obr. 10. Počet postupností aspoň 5 suchých dní.

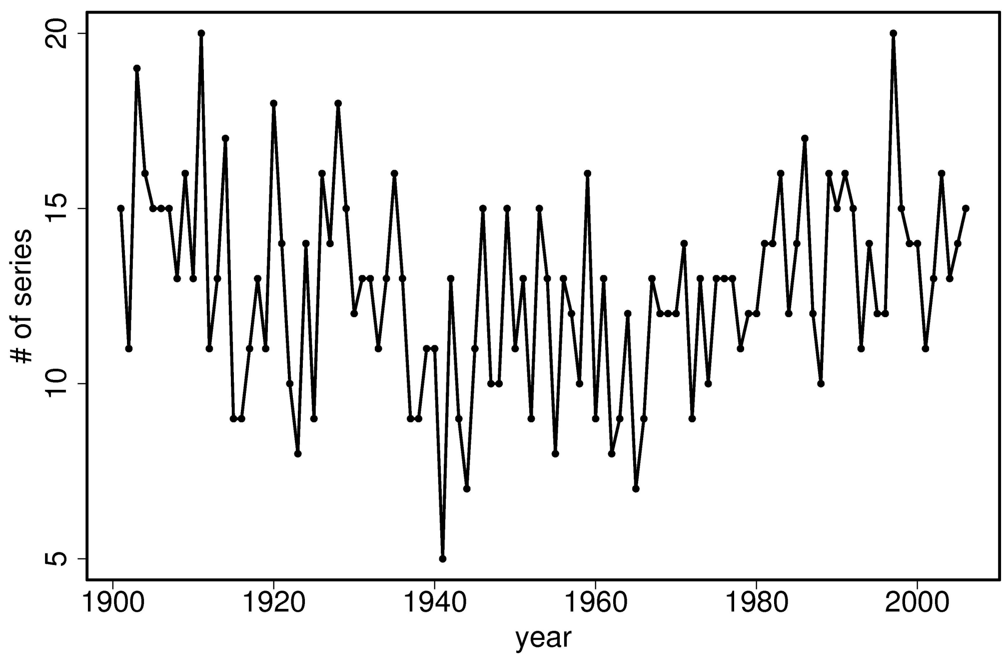


Fig. 11. Number of series of at least 15 days with precipitation totals under 1 mm.
Obr. 11. Počet postupností aspoň 15 dní s úhrnom zrážok do 1 mm.

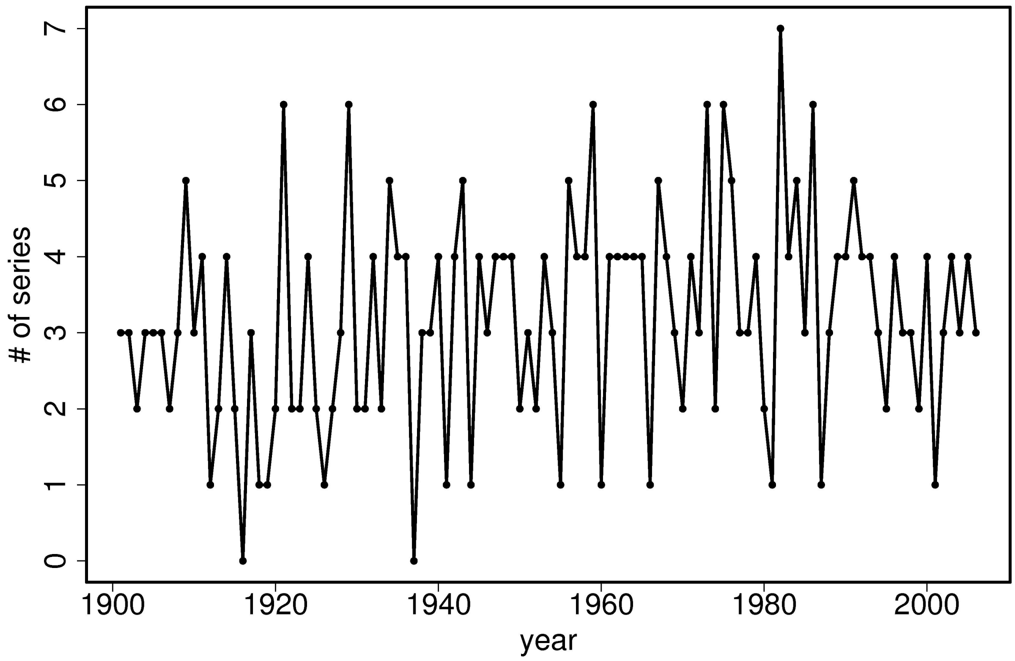


Fig. 12. Number of series of at least 30 days with precipitation totals under 5 mm.
Obr. 12. Počet postupností aspoň 30 dní s úhrnom zrážok do 5 mm.

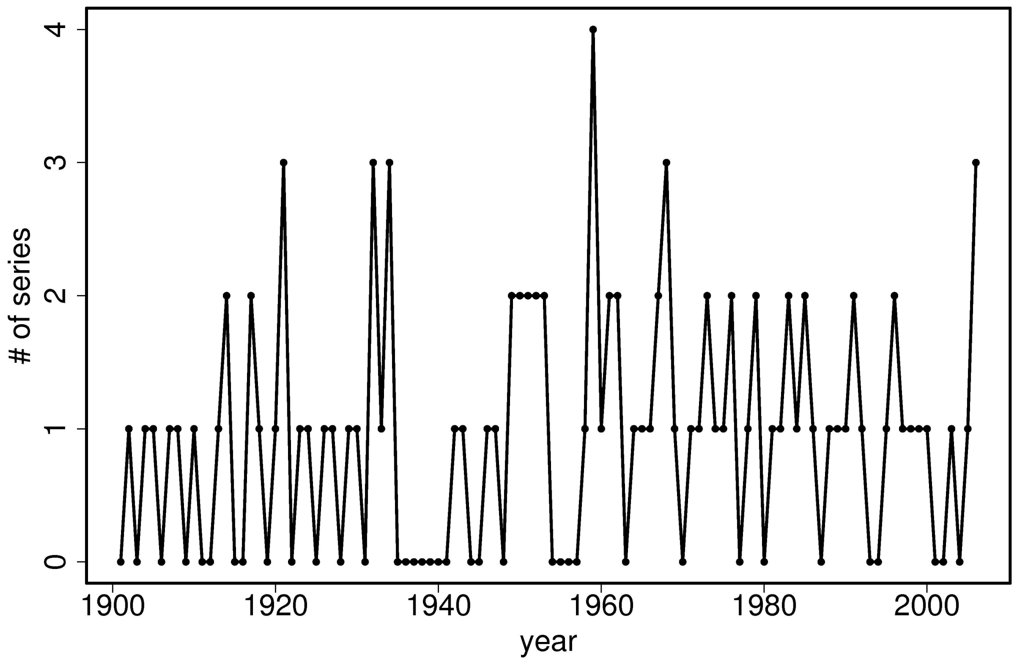


Fig. 13. Histogram of drought indices and the sample 95% quantile.
Obr. 13. Histogram indexov sucha a výberový 95% kvantil.

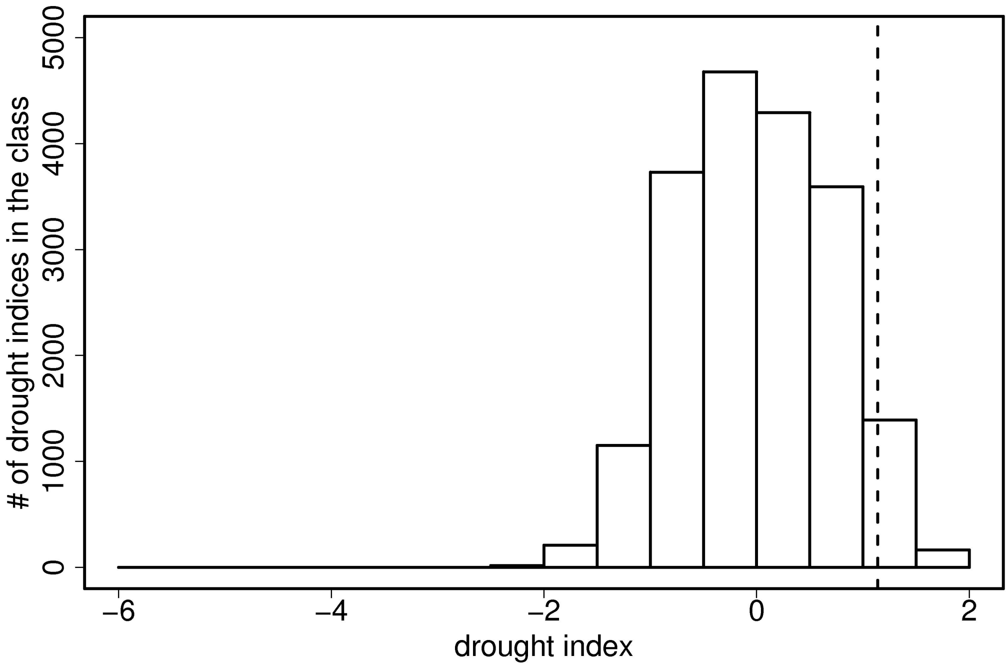
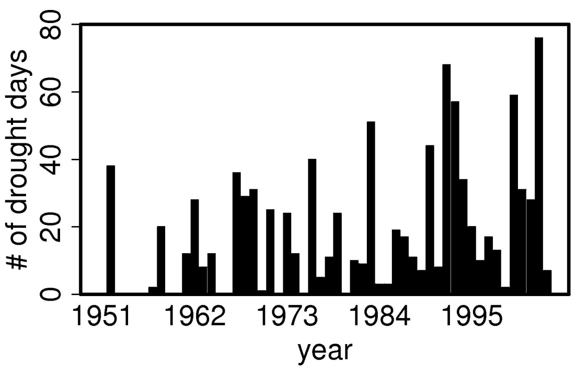


Fig. 14. Number of drought days in corresponding years (left) and monthly distribution (right).
Obr. 14. Počty suchých dní v príslušných rokoch (vľavo) a mesačné rozloženie (vpravo).



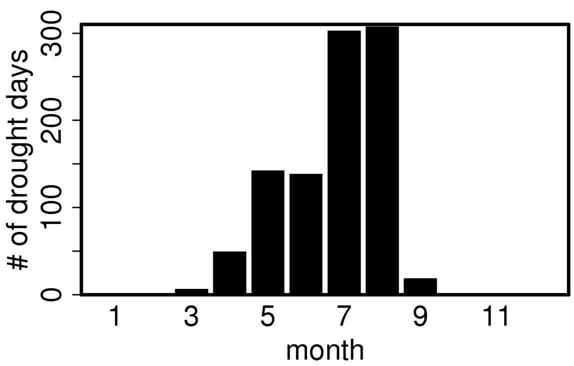


Fig. 15. Growing season (April-September): number of drought days in corresponding years (left) and monthly distribution (right).
Obr. 15. Vegetačné obdobie (apríl-september): počty suchých dní v príslušných rokoch (vľavo) a mesačné rozloženie (vpravo).

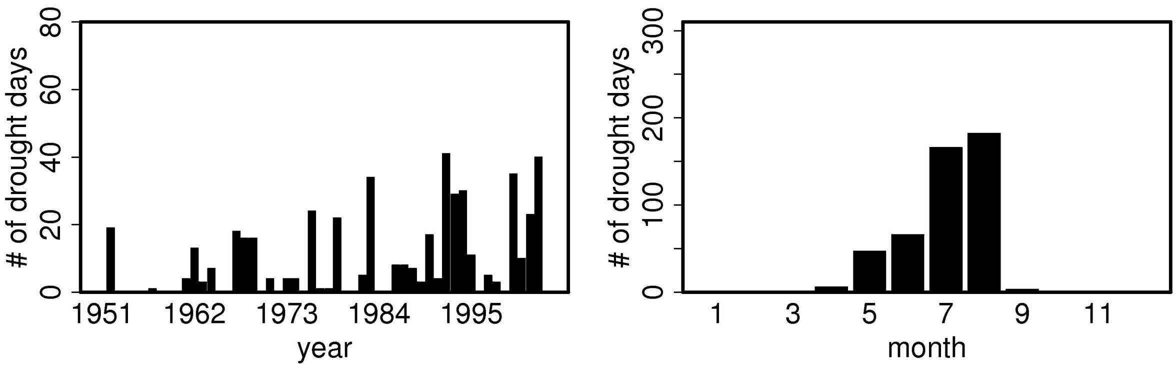


Fig. 16. Alternative method of indication of drought days (growing season April-September): number of drought days in corresponding years (left) and monthly distribution (right).
Obr. 16. Alternatívna metóda určenia suchých dní (vegetačné obdobie apríl-september): počty suchých dní v príslušných rokoch (vľavo) a mesačné rozloženie (vpravo).

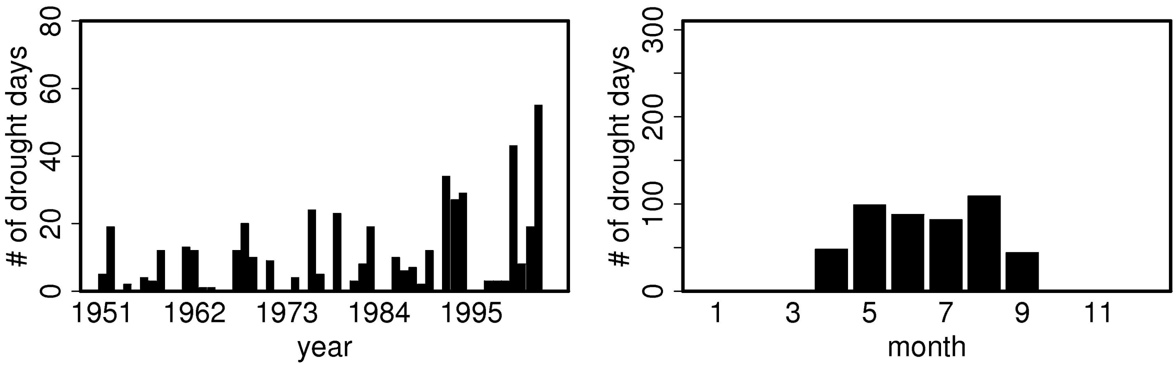


Fig. 17. DEA method: number of extreme days in corresponding years (left) and monthly distribution (right).
Obr. 17. DEA metóda: počty extrémnych dní v príslušných rokoch (vľavo) a mesačné rozloženie (vpravo).