# Spatial Discretization of the Nesterov Fire Rating Index using Multispectral Satellite Imagery


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## INTRODUCTION

Fire-risk rating indices rely on statistical relationships between pre-event meteorological conditions and the observed number of fire outbreaks. However, such indices do not provide information on the spatial distribution of fire-susceptible sites within a forest because these provide only an area-averaged value of the risk of fire. This disadvantage can be relieved by using remote sensing data. We present our data on a set of four Landsat ETM+ scenes taken over a forested area (dominated by Pinus sylvestris) in western Slovakia. Our investigation suggests that coupling the Temperature-Vegetatin Dryness Index – TVDI (Sandholt et al., 2002) with traditional weather-based fire indices can become an effective tool for delineating areas prone to fire outbreaks, particularly because TVDI can facilitate the allocation of fire-fighting sources in inaccessible forested areas.

## MATERIALS AND METHODS

### STUDY AREA

The geographical setting of the region of interest in illustrated in Fig. 1. This area is located between 48°20'N 17°E and 48°50'N 17°30'E; northerly of the capital city of Bratislava, Slovakia. This region is dominated by vast patchy areas (totally ~44 000 ha) of coniferous stands (dominated by Pinus sylvestris) growing on sandy soils (90 % quartz). Some 35 % of the forested area is formed by natural stands, and 65 % occupy cultural forest plantations. The prevailing north-westerly winds (annual average: 2.8 m/s) and low annual precipitation rates (~554 mm) make these forests sensitive to fire events.

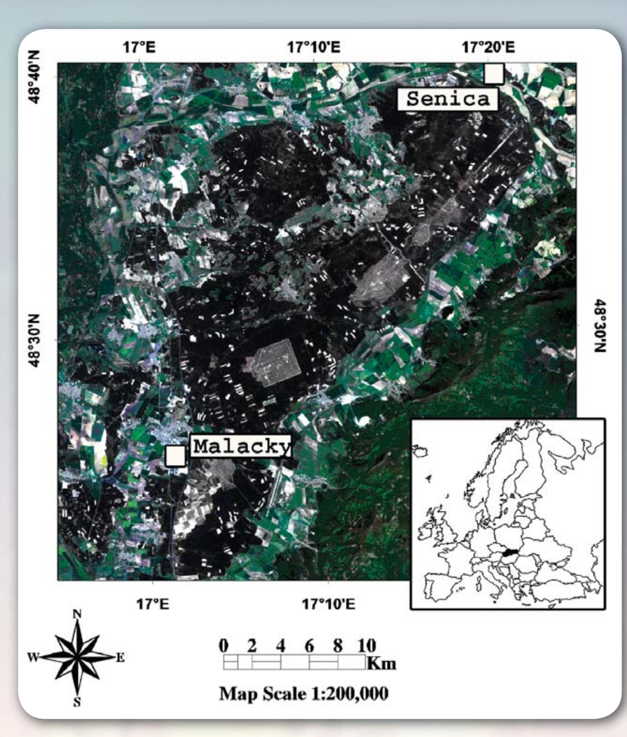


*Figure 1. Area setting with local weather-stations (Malacky and Senica).*

### TEMPERATURE / VEGETATION DRYNESS INDEX

To establish a spatially variable attribute of the Nesterov Index we focused on the work of Sandholt et al., 2002. The concept of "Ts-Vegetation Space" was originally proposed to assess the soil moisture status of vegetation. In principle, the Ts-Vegetation Space represents a scatter-plot of remotely sensed surface temperature and NDVI collected form a sample area with a broad range of moisture conditions. Evidence exists that a strong negative relationship between radiometric surface temperature and NDVI; which was explained by evaporative cooling of green live biomass. When surface conditions become drier, vegetated areas transpire less water, and, when a drought period prevails for a sufficiently long time, NDVI values decrease and surface temperature tends to increase due to hindered evaporative cooling. Fig. 4 explains the Temperature/Vegetation Dryness Index (TVDI) in detail. Calculation of the Temperature/Vegetation Dryness index is based on the following equation:

$$TVDI = \frac{T_S - T_{S\_min}}{a + b \times NDVI - T_{S\_min}} \qquad (2)$$

where: $T_s$ is the surface temperature
$T_{s\_min}$ is the minimum surface temperature in the triangle necessary to define the "wet edge"
NDVI is the normalized differencial vegetation index a and b are parameters derived from a linear fit to
$T_{s\_max} = a + bNDVI$

Note that the triangle in Fig. 4 is enclosed by two curves: the upper curve, called the "dry edge"; and the lower curve, called the "wet edge". The "wet edge" and "dry edge" in the triangle (Fig. 4) represent the TVDI boundary values. TVDI equals zero on the wet edge, and unity (1) on the dry edge. All TVDI values between these two edges may therefore take values only in the range 0-1.

### NESTEROV INDEX

In 1949, Nesterov (Shetinsky, 1994) proposed a fire-risk rating index to be used in the continental former Soviet Union. This index establishes a range of discrete fire risk levels. The Nesterov Index is calculated as follows:

$$NI = \sum_{i=1}^{w} (T_i - T_i^{dew}) T_i \qquad (1)$$

where NI denotes the Nesterov Index; w is the number of days since the last rainfall exceeding 3 mm/day, i is the temperature (°C) on a given day; and $T_i^{dew}$ is the dew point temperature (°C). The intrinsic characteristic of the Nesterov Index is that it is reset to "zero" when daily rainfall exceeds 3 mm a day. Fig. 3 illustrates the workings of the Nesterov Index. After each rainfall exceeding 3 mm a day (the upper horizontal axis in Fig. 3), the index drops to zero.

NI was calculated on a daily basis for the period between Jan 2, 1999 to April 30, 2002 (Senica Station, Fig. 1); and between Jan 1, 1999 and August 31, 2004 (for the Senica Station, Fig. 1). Daily average of the input weather data were acquired from the Slovak Meteorological Institute. To make sure that the original risk levels of NI are suitable for the investigated region, we benefited from the Slovak national databases (1998-2003) of forest fires and meteorological data obtained from two weather stations in the investigated region to redefine the discrete levels of the Nesterov Index. Fig. 2 shows the probability of fire occurrence in the investigated area in relation to the NI. The input data for the NI were obtained from two weather stations located near the forested area (denoted as "Malacky Station" and "Senica Station"). These two datasets were averaged to obtain the fire risk for the entire area. The probability plot was apportioned into four levels of fire risk with 25 % increments of probability: low risk (NI<300; P<30 %), medium risk (NI [300, 3300]; P<50 %), elevated risk (NI [3300, 4400]; P>75 %), and high risk (NI > 4400; P> 75 %). Note that the calculated values of the NI for the area of interest and the period of record never exceeded 5000. In order to be able to differentiate between a sufficient number of risk levels, the range of NI (0-5000) was divided according to the probabilities with 25 % increments.

## RESULTS

Four Landsat ETM+ images were used to derive the TVDI index. Sub-images of the distribution of TVDI on the dates of satellite overpass are depicted in Fig. 6. Note that the TVDI index is highly variable between the four investigated images. As shown in Table 1, NI may differ between two weather station may be quite different despite the relative short distance between them (~35 km). This difference may be explained by the fact that precipitation is a highly variable phenomenon; i.e. there may be summer storm formation in one area, while a few kilometers away there is no rainfall. This is evident in Table 1 listing the calculated Nesterov Index for the analyzed dates. For example, on May 14, 2000, at the Malacky weather station the NI was 5156, while at the Senica Station the IN was 1224. Therefore, relying merely on the NI derived from only one weather station may lead to misleading levels of fire-risk if the spatial character of the index is not taken into account. Using the Nesterov Index (or any other fire rating index based on meteorological data) in synergy with the TVDI may be beneficial in terms of assigning each pixel in a satellite image an intrinsic fire risk value (Fig. 6). The fire data were analyzed for the period between Jan 1, 1999 and April 30, 2002 (Malacky County), and for the period between Jan 1, 1999 and June 30, 2004 (Senica County). Fig. 3 shows the positive correlation between the value of NI and the probability of fire occurrence. Probability of fire increases with increasing NI. The empirical probability of fire outbreak in the Senica County approaches 100 % for NI>4100 (Fig.2). A cumulative probability curve has been averaged from these two stations (Malacky and Senica). The interval of probabilities was divided into four discrete levels: low risk (NI>250; P>25 %), medium risk (NI [250, 3300]; P<50 %), elevated risk (NI [3300, 4400]; P<75 %), and high risk (NI > 4400; P> 75 %). Note that the TVDI index can yield values only in the range 0-1. Dividing this interval into three equal subintervals (0-0.33; 0.33-0.66; and 0.66-1.0) made it possible to roughly differentiate between pixels with "low" – "moderate" and "high" risk of fire outbreak. Sites with higher TVDI show where the risk of fire occurrence is more "probable". Linking this value to the TVDI map calculated for the May 1, 2001 (Fig. 6) shows that the risk was not equally distributed over the investigated area. A cumulative probability curve has been averaged from these two stations.

| Date | NI (Malacky Station) | NI (Senica Station) | Average NI |
|---|---|---|---|
| May 14, 2000 | 5156 | 1224 | 3190 |
| August 2, 2000 | 404 | 351 | 377.5 |
| May 1, 2001 | 1175 | 920 | 1047.5 |
| August 24, 2002 | 731 | 1252 | 991.5 |

*Table 1. Nesterov Index calculated for the dates of satellite image acquisition for the two weather stations (Malacky and Senica).*

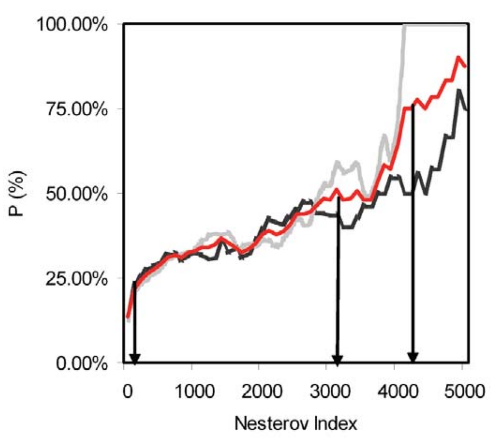


*Figure 2. Probability plot of fire risk in relation to the Nesterov Index. Definition of site-tailored risk levels (arrows).*

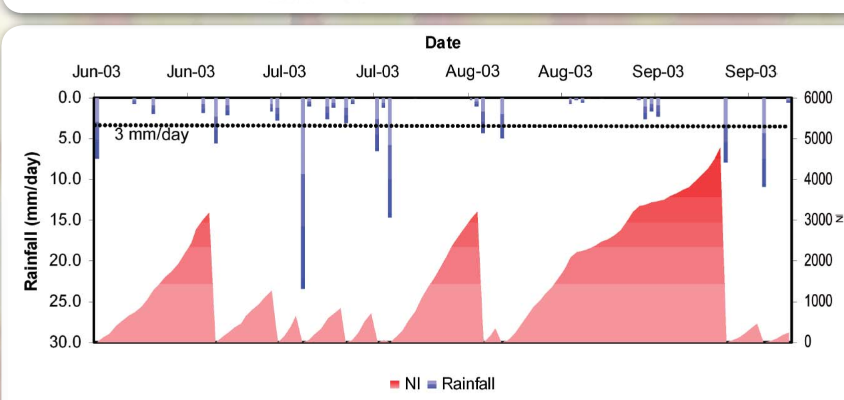


*Figure 3. Daily series of rainfall and the Nesterov Index "NI" (June-October, 2003; Senica Station). Minimum rainfall (dashed line) at which the Nesterov Index is reset.*

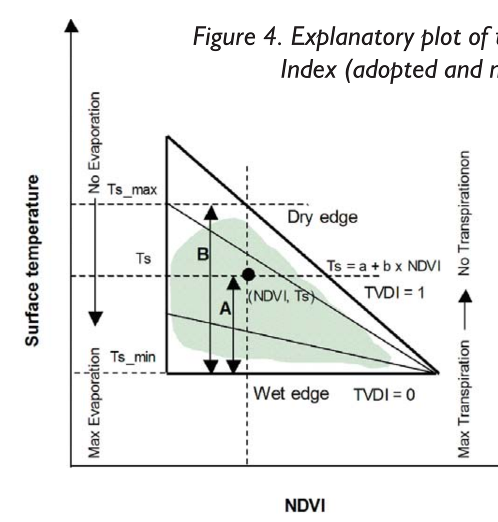


*Figure 4. Explanatory plot of the Temperature/Vegetation Dryness Index (adopted and modified from Sandholt et al., 2002).*

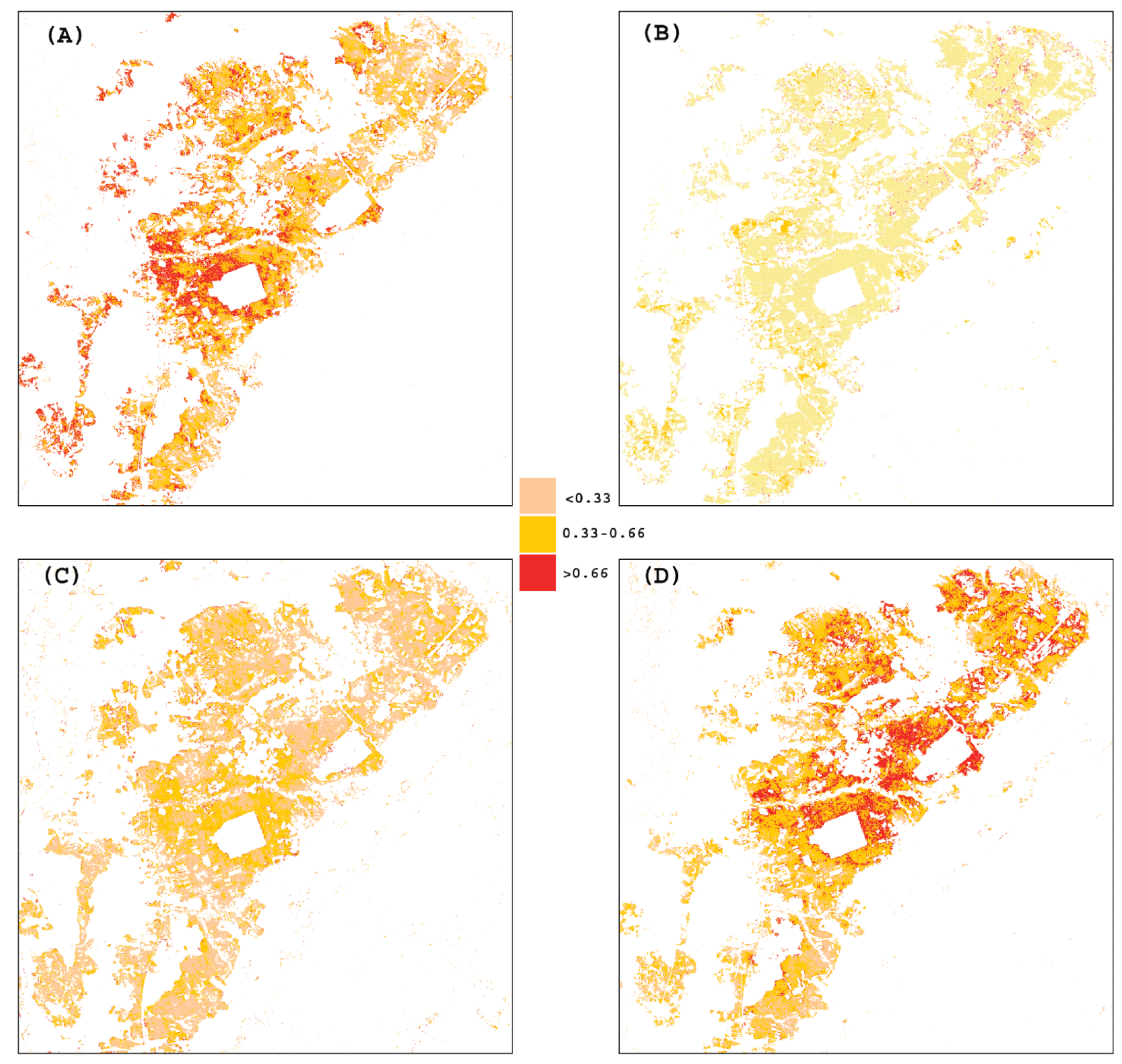


*Figure 6. Distribution of TVDI on A – May 1, 2001; B – May 14, 2000; C – August 2, 2000; D – August 24, 2002. For clarity, non-forest areas were masked out. TVDI levels are differentiated by color: red (0.66<TVDI<1.0); orange (0.33<TVDI<0.66); and pink (0<TVDI0.33).*

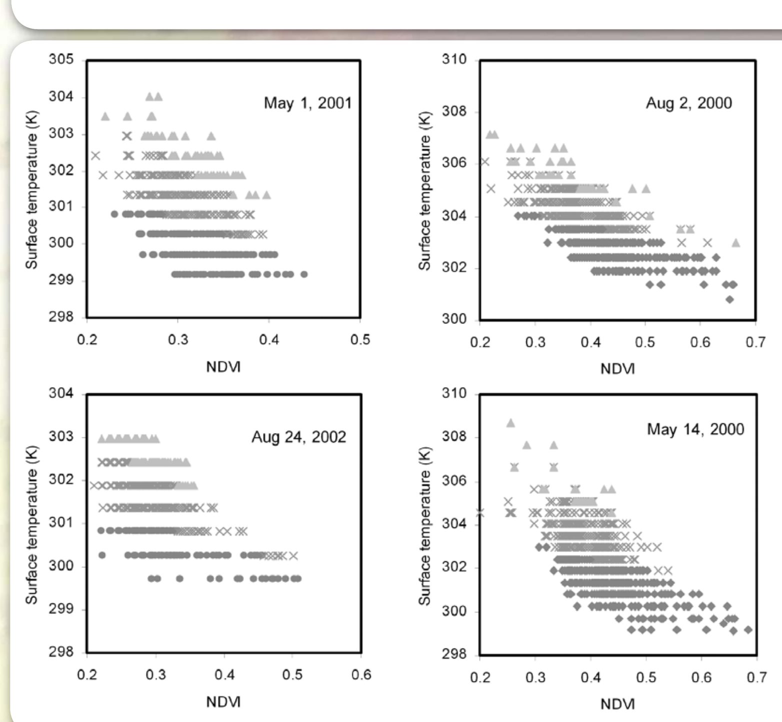


*Figure 5. TVDI scatterplots for the dates of image acquisition (May 1, 2001; May 14, 2000; August 2, 2000; and August 24, 2002). Legend: • TVDI ▲(0-0.33); × TVDI ▲(0.33-0.66); ▲ TVDI ▲(0.66-1.0).*

## CONCLUSIONS

The presented methodology may find its application in areas where weather-stations are installed across large distances. In such instances, the calculated Nesterov Index (or any other weather-based index) may yield misleading results in terms of its spatial representativenes. Remotely sensed data may be used as supplementary attribute useful for delineating sites with dry fuel conditions.