

Definition of Spatial Patterns of Bark Beetle *Ips typographus* (L.) Outbreak Spreading in Tatra Mountains (Central Europe), Using GIS

Rastislav Jakuš¹, Wojciech Grodzki², Marek Ježík¹, Marcin Jachym²

¹Institute of Forest Ecology, Slovak Academy of Sciences, Zvolen, Slovakia

²Forest Research Institute, Kraków, Poland

Abstract

The spread of bark beetle outbreaks in the Tatra Mountains was explored by using both terrestrial and remote sensing techniques. Both approaches have proven to be useful for studying spatial patterns of bark beetle population dynamics. The terrestrial methods were applied on existing forestry databases. Vegetation change analysis (image differentiation), digital elevation model, and stand characteristics have been integrated in the remote sensing part of the study. Results have revealed that the spatial pattern of bark beetle spread depends on the phase of the outbreak and on the insolation (amount of incoming solar radiation) of stands on mountain slopes and, specifically on the bark beetle spots themselves.

Introduction

The Tatra Mountains are located in the Western Carpathians on the border between Slovakia and Poland. The entire area of the Tatra Mountains has been designated as a protected area – comprising two National Parks: Tatrzński Park Narodowy (TPN) in Poland and Tatranský Národný Park (TANAP) in Slovakia.

In 1995-97, a serious outbreak of the spruce bark beetle *Ips typographus* (L.) (Col.: Scolytidae) occurred in the Norway spruce stands of the Tatra Mountains, on both the Polish and Slovak sides of the border (Fig. 1). This insect, recognized as the most serious pest associated with Norway spruce stands, caused dramatic tree mortality in the region of Łysa Polana – Morskie Oko – Tatranská Javorina. On the Polish side, in stands which are under a strict protection regime, mature Norway spruce stands died over large areas; on the Slovak side, where several different forest protection strategies were applied, many entire stands of Norway spruce had to be felled.

Materials and Methods

We used both terrestrial and remote sensing techniques to conduct spatial analyses of the spread of *I. typographus* outbreaks.

Terrestrial Approach

We initiated our research by creating rich databases which contained detailed information about the characteristics of stands and bark beetle populations. Information on site characteristics, stand composition and age, and annual tree mortality during the period 1990-1999 was acquired from the administrative offices of the Tatrzński Park Narodowy (TPN – Poland) and Tatranský Národný Park (TANAP – Slovakia). The smallest units of data that were used in our research consisted of forest sub-compartments. The data concerning tree mortality was transformed into tree mortality indices (TMI) and expressed as the mean volume of infested trees per one hectare in the sub-compartment (m³/ha). The data were ranked according to a somewhat adjusted scale developed by Capecki (1981), with the following ranges of mortality in m³/ha: 0.01-0.4 – normal, 0.41-1.2 – premonitory, 1.21-2.4 – intensive, 2.41-10.0 – very intensive, >10.0 – catastrophic.

The digital map with a DTM, covering the research area (Koreň et al. 2002), and the layers concerning tree mortality, were constructed using a vector oriented software ArcView 3.1. The layers on tree mortality (TMI) in successive years were used to produce a visualization of spread of bark

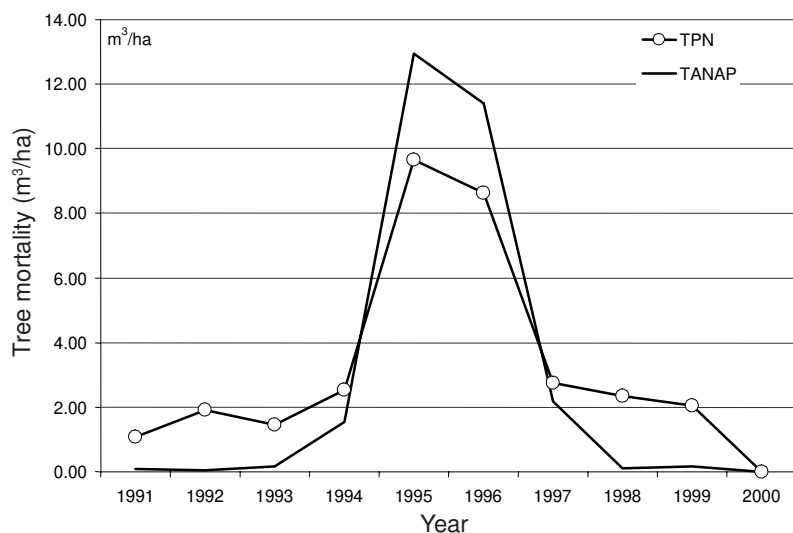


Figure 1.—Intensity of bark beetle outbreaks in the Tatra Mountains expressed through mean tree mortality (m^3/ha) caused by bark beetle attacks in 1991-2000 in Polish (TPN) and Slovak (TANAP) parts of the study area.

beetle outbreaks. The total area of attacked stands, i.e. the area of all sub-compartments with recorded trees attacked by bark beetles in a year, were derived from the database.

Remote Sensing Approach

The time series of LANDSAT images for years 1991, 1993, 1995, 1997, 1999, a digital elevation model, and other GIS data obtained from Koreň et al. (2002), were processed by using by a raster oriented GIS program IDRISI 32.

Identification of Bark Beetle Spots

Based on the summarized data, we prepared a mask of spruce forest cover on the geographical area under study. This mask was used for localization of work to spruce stands. First we tried to identify bark beetle spots on the time series of LANDSAT images with the aid of standard classification methods, however this approach was not successful. Later we used the vegetation change analysis and the method of image differentiation (Eastman et al. 2000). This research was applied during the periods: 1991 - 1993, 1993 - 1995, 1995 - 1997, 1997 - 1999.

The work was intricate, which was caused by the presence of shadows cast within the mountain environment. We tried to resolve this problem by applying an approach which integrated remote sensing and GIS tools. A pilot study comparing areas with cast shadows and areas containing bark beetle spots showed that there was no overlay between these two categories. *I. typographus* did not attack forests that occurred on steep North - oriented slopes (Fig. 3) with cast shadows. This determination allowed us to exclude the areas with cast shadows from our interest in bark beetle spot identification.

The selection of suitable vegetation indices was obtained through our conduct of a special literature review. We selected the following indices: Normalized Difference Vegetation Index, Specific Leaf Area Vegetation Index, Vegetation Condition Index, Greenness Condition Index, and Normalized Ratio Vegetation Index. The change analyses were performed using the maps of all the above vegetation indices. The resultant maps were compared with several forest compartment maps and with the data obtained on bark beetle damage (Fig. 2). Only the Vegetation Condition Index ($\text{TM7} / \text{TM4}$; Jakubauskas, Price 1997) was found to be a usable characteristic. The resultant maps were then compared with aerial infrared photographs of the study area taken by the Research Station of the Tatra National Park in 1999.

Spatial analyses

We used spatial analyses to investigate the processes of spot initiation and spot spreading. Our analyses of vegetation change allowed us to distinguish three phases in the development of bark beetle outbreaks (progradation: 1991 - 1993, 1993 - 1995; culmination: 1995 - 1997; retrogradation 1997 - 1999.)

a) Spot initiation: By examining images indicating areas of bark beetle damage, we were able to differentiate between new (initiated in the current year) and old (initiated in any of the previous years) spots, and to calculate the areas of both. We then measured the shortest distances between the new and old spots. The data obtained were transferred into the statistical software STATISTICA for further analyses.

b) Spot spreading: Direction and speed of spreading were calculated for increasing bark beetle spots. The calculations were performed with the use of surface functions (IDRISI) and trigonometry for every pixel of the areas examined. Speed of spreading was measured only on the active (increasing) spots; spots with no expansion were excluded from consideration. Further analyses were performed using raster data at the pixel level, meaning we measured parameters for pixels belonging only to particular spots (one spot could be covered by several pixels). Then the data were subjected to the statistical analyses using STATISTICA software.

Results

Terrestrial research

The well-designed and developed database was used for assessing the course of *I. typographus* outbreaks over time on both sides of the state boundary (Table 1). The level of tree mortality remained relatively constant during the entire outbreak period (Spearman's rank correlation $r_s=0.91^{***}$); however, both the degree of mortality and the area of stands attacked changed more dramatically on the Slovak portion of the area studied, especially during the period 1995-1996 when intensive sanitary cuttings were deployed.

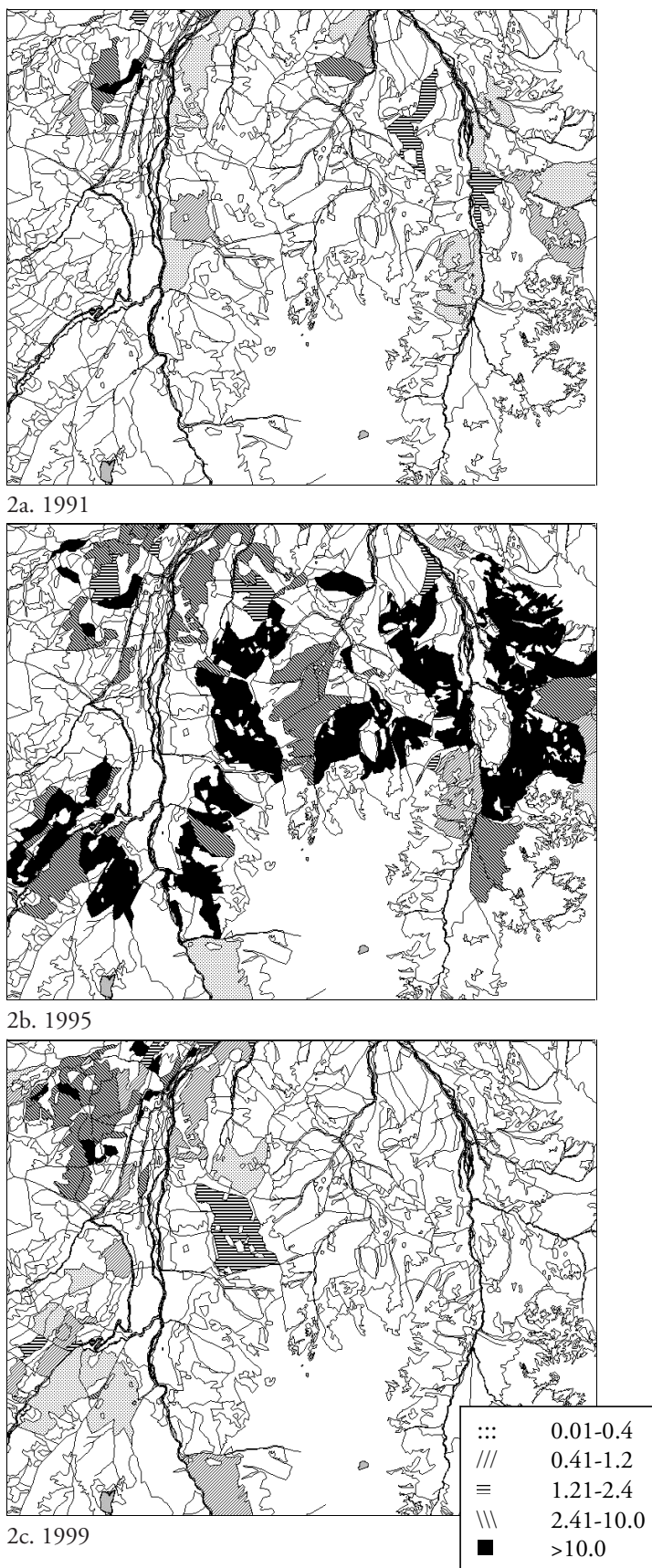


Figure. 2 a-c.—Spatial development of the bark beetle outbreak in the Tatra Mountains in 1991 (a), 1995 (b) and 1999 (c), with the degree of tree mortality (m³/ha) in the individual forest sub-compartments.

Table 1.—Area (ha) of stands attacked by bark beetles, derived from the database

year	TPN	TANAP
1991	387.92	297.22
1992	544.58	224.30
1993	567.55	364.91
1994	672.80	897.34
1995	712.24	1435.29
1996	816.64	1453.52
1997	727.77	1216.60
1998	768.60	92.02
1999	741.53	306.40

The outbreak began on several sites that were separated geographically and distributed throughout the entire study area (Fig. 2a); during the culmination phase, most of the stands in the entire study area were attacked (Fig. 2b), whereas during the retrogradation phase, attacks receded to certain stands close to the state boundary and to the initial outbreak area (Fig. 2c). The distribution of the most seriously attacked stands based on their exposition is shown in Figure 3. Data on the localization of *I. typographus* spots provided by TPN services and based on terrestrial estimations, and data on the distribution of attacked sub-compartments, had been overlaid on the map with vegetation types. However, the classification of vegetation types currently used in Poland was very simplified as compared to the much more elaborate differentiation of forest vegetation types used in Slovakia. Consequently, use of this classification was possible only in Poland. In the Polish stands attacked by *I. typographus* and belonging to only two forest types (*Abietetum* and *Piceetum tatricum*) occurring in two altitudinal zones (upper and lower mountain zone), we observed no distinct differences in attack intensity related to vegetation type/altitudinal zone.

Remote sensing approach

The map of damage caused by the spread of bark beetle populations is provided in Fig. 4. The comparison between this map and infrared aerial photographs demonstrated that 99% of bark beetle spots visible on the aerial photos had also been identified by vegetation change analysis of the LANDSAT time series. Therefore, the map was used in further analyses.

a) Spot initiation: Spatial analyses have shown that the area of new spots was larger than the area of old spots during the progradation phase (Fig. 5). Incidence of tree mortality was linked mainly with spot initialization. During the culmination and retrogradation phases, the area of new spots was considerably smaller than the area of old spots. In this case, the mortality was caused primarily by the expansion of old spots. The distances between new and old spots decreased during the course of the outbreak (Fig. 6).

b) Spot spreading: The spots were spread in all directions except south (Fig. 7). The speed of active spot spreading increased during the outbreaks (Fig. 8).



Figure 3.—Distribution of the volume of infested trees (% of total) on mountain slopes in the Slovak (TANAP) and Polish (TPN) parts of the study area.



Figure 4.—Map of the spread of bark beetle outbreaks based on satellite image analysis

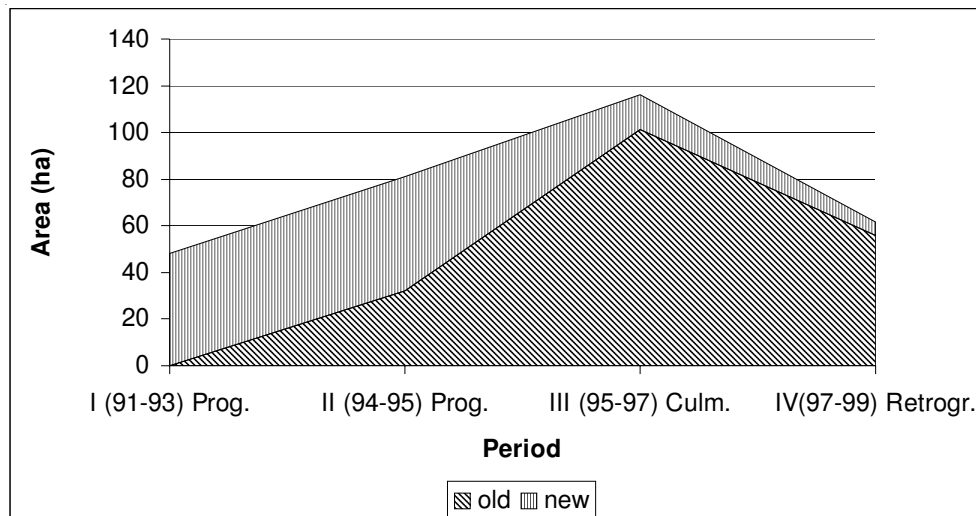


Figure 5.—Area of new and old bark beetle spots in different phases of bark beetle outbreaks

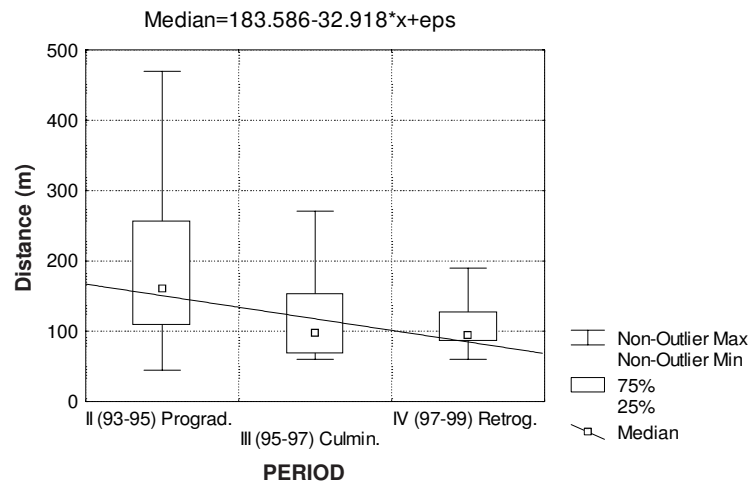


Figure 6.—Minimum distances between new and old spots.

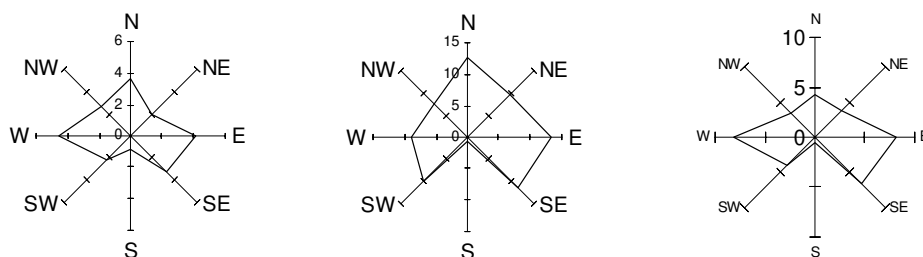


Figure 7.—Direction of spread of spots (ha of damaged area).

Discussion

Methodology

Both approaches utilized (terrestrial & remote sensing) have demonstrated their usefulness for studying the spatial dynamics of bark beetle populations. The terrestrial approach can be applied using data acquired through common forestry practices used in both Poland and Slovakia and therefore is relatively inexpensive. Digital maps of forest stands will be made available to foresters in the near future. The main disadvantage of this approach is its low spatial resolution (compartment). The remote sensing approach requires the use of spatial methods for processing satellite images and the availability of digital elevation models and thematic maps. All these technologies are quite expensive, however the remote sensing approach provides a much higher spatial resolution (30 m for LANDSAT images).

A fairly high accuracy in identifying bark beetle spots (about 99%) was achieved by combining information obtained from both LANDSAT images and from the thematic databases. Zemek et al. (1999) achieved 89% accuracy in classifying an area affected by a bark beetle outbreak in the NP Šumava, using classical remote sensing data. We have achieved relatively good results with our method, however it places a higher demand on the quality and quantity of thematic information and time series of LANDSAT images.

The Expansion of Bark Beetle Outbreaks

The general pattern in which *I. typographus* outbreaks spread agrees with descriptions of other authors (Schwerdtfeger 1955, Stolina 1970, Capecki 1978). The distribution of most frequently attacked stands based on their exposure reflects the general distribution of slopes in both parts of the studied area. Nevertheless, attacked stands are distributed more southward and eastward, which agrees with observations of *I. typographus* outbreaks from other mountain areas (Grodzki 1997). Our results have shown that during progradation phase of the outbreak, the spread arises mainly from new bark beetle spots. In the culmination and retrogradation phases, outbreaks spread by further expansion from old spots. Lohberger (1993) revealed that 69% of the spots studied during the period 1988 - 1991 in the NP Bayerischer Wald were spread from old spots while only 6% of spots were attacked only in the first year. Thus, the dominance of continuous growth of spots could be characteristic of *I. typographus* outbreaks and could explain the dominance of old spots that we observed in later outbreak stages in the Tatra Mountains.

We have recorded time-dependence of a decrease in the distances between old and new spots. In the first stage of the outbreak, the beetles migrated over fairly long distances and explored available resources. The area containing stressed trees that were susceptible to being attacked was quite large. In later stages, the available resources were more limited, thus the beetles were more likely to attack only less suitable resources adjacent to old spots. We found that the distances that we measured between old and new attacked spots were similar to those measured by Wichman and Ravn (2001). Otto and Schreiber (2001) recorded almost equal distances between the currently attacked spots and the spots attacked in the preceding years, however, the distances were almost two times further than the

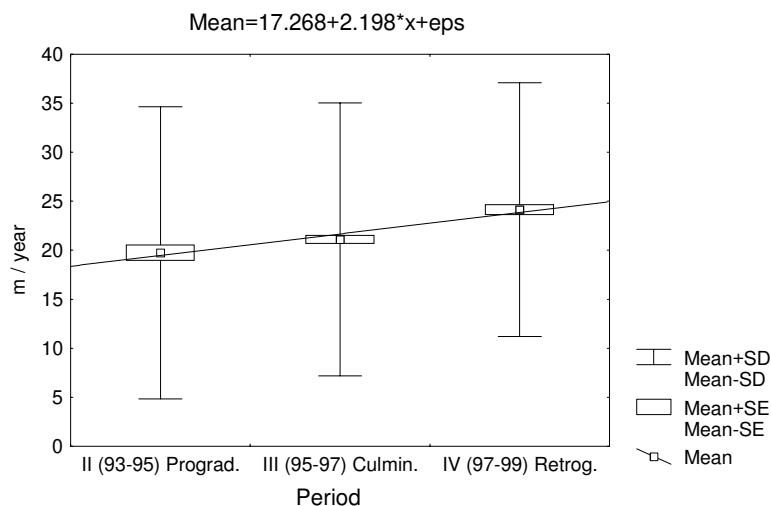


Figure 8.—Speed in which active spots spread.

distances that we measured in the Tatra Mountains Time-dependent differences in distances can be explained by the existence of a lower outbreak intensity, consequently beetles probably had not utilized the majority of the resources available. The aforementioned authors recorded their distances in an outbreak that occurred at lower elevations and under climatic conditions that were optimal for bark beetle development. The outbreak in the Tatra Mountains took place at relatively high elevations and in an area that is not suitable for outbreaks. The smaller distances that we recorded in the Tatra Mountains can be explained by the fact that the outbreak area was characterized by high mountain chains without vegetation that provided a separation between the attacked spots.

The direction in which spots spread was in agreement with Lohberger (1993). Beetles preferred to attack trees at forest edges exposed to solar radiation. According to Schopf and Köhler (1995), the main factor influencing the spread of outbreaks is the stress on trees caused by an abrupt increase in the level of solar radiation. This increase of solar radiation can result from cutting, downing or defoliation of neighboring trees. Trees on forest edges with a northern exposure were not stressed. Thus there were almost no attacks spreading in a southerly direction (that means attacks at forest edges exposed to the North) from initial bark beetle spots.

The increase in the rate of spread of active bark beetle spots during of the course of the outbreak could be explained by the expansion of old spots over time.

Conclusions

1. The spatial pattern of the spread of bark beetle outbreaks is related to the phase of the outbreak, to the insolation (incoming solar radiation) of stands on mountain slopes, and – primarily – the insolation of the individual bark beetle spots.
2. The integration of vegetation change analysis (image differentiation), a digital elevation model, and information about stand characteristics, provides a reliable method that can be used for mapping intensive bark beetle outbreaks in mountainous conditions.
3. These results demonstrate the usefulness of such approaches for conducting research on bark beetle outbreaks in mountain conditions, and for applying forest (nature) protection practices.

Acknowledgments

The research was supported by EU-INCO project: Integrated risk assessment and new pest management technology in ecosystems affected by forest decline and bark beetle outbreaks, and by the Grant Agency for Science of Slovak Academy of Sciences (2/1162/21). The authors wish to thank foresters from both national parks and Eva Lajzová for help with data acquisition and Dr. Kúdelová for correction of the English grammar.

References Cited

- Capecki Z. 1978.** Badania nad owadami kambio- i ksylofagicznymi rozwijającymi się w górskich lasach świerkowych uszkodzonych przez wiatr i okiść. *Prace Inst. Bad. Leśn.*, 563: 39-117.
- Capecki Z. 1981.** Zasady prognozowania zagrożenia oraz ochrona górskich lasów świerkowych przed owadami na tle szkód wyrządzanych przez wiatr i okiść. *Prace Inst. Bad. Leśn.* Nr 584: 3-44.
- Eastman, J. R.; McKendry, J. E.; Fulk, M. A. 2000.** Change and Time series analysis. (United Nations Institute for Training and Research, Explorations in Geographic Information Systems Technology, Volume 1), Clark University, Worcester, CD.
- Grodzki W. 1997.** Changes in the occurrence of bark beetles on Norway spruce in a forest decline area in the Sudety Mountains in Poland. Pp 105-11 in J.-C. Gregoire, A.M. Liebhold, F.M. Stephen, K.R. Day, and S.M. Salom (Eds.), *Proceedings of the IUFRO conference, Integrating cultural tactics into the management of bark beetles and reforestation pests*, Vallombrosa 1-4 september 1996. USDA, Forest Service General Technical Report NE-236.
- Jakubauskas, M. E.; Price, K. P. 1997.** Empirical relationship between structural and spectral factors of Yellowstone lodgepole pine forests. *Photogrammetric Engineering & Remote Sensing*, 63 (12): 1375-1381.
- Koreň et al. 2002.** Building of a GIS database. In: Integrated risk assessment and new pest management technology in ecosystems affected by forest decline and bark beetle outbreaks. (Final report from INCO-Copernicus European research project).
URL: http://www.vsv.slu.se/schlyter/tatry_pr/tatrypr.htm
- Lohberger, E. 1993.** Zur Populationsdynamik von *Ips typographus* L. im Nationalpark Bayerischer Wald: Entstehung und Entwicklung von ausgewählten Befallsflächen im Lusengebiet. Diplomarbeit der Forstwissenschaftlichen Fakultät der Ludwig-Maximilians-Universität München. 80 pp.
- Otto, L. F.; Schreiber J. 2001.** Spatial patterns of the distribution of trees infected by *Ips typographus* (L.) (Coleoptera, Scolytidae) in the National Park „Sächsische Schweiz” from 1996 to 2000. *Journal of Forest Science*, 47 (Special Issue No. 2): 139 - 142.
- Schopf, R.; Köhler, U. 1995.** Untersuchungen zur Populationsdynamik der Fichtenborkenkäfer im Nationalpark Bayerischer Wald. In: Biberliether, H. at al.: 25 Jahre auf dem Weg zum Naturwald. Passavia Druckerei GmbH, Passau, p. 88-109.
- Schwerdtfeger, F. 1955.** Pathogenese der Borkenkäfer-Epidemie 1946 - 1950 in Nordwestdeutschland. Schriftenreihe der Forstlichen Fakultät der Universität Göttingen und Mitteilungen der Niedersächsischen Forstlichen Versuchsanstalt. 13/14. 133s.
- Stolina, M. 1970.** On the problem of indifference of *Ips typographus*. *Zborník vedeckých prác Lesníckej fakulty VŠLD vo Zvolene*. 12 (3): 61-76. (In Slovak).
- Wichmann L., Ravn, H. P. 2001.** The spread of *Ips typographus* (L.) (Coleoptera, Scolytidae) attacks following heavy windthrow in Denmark, analysed using GIS. *Forest Ecol. Mgmt*, 148: 31-39.
- Zemek, F., Heřman, M., Klouda, Z. 1999.** Bark beetle calamity assessment from remotely sensed data. *Silva Gabreta*. 3: 191-172.