Geostatistical simulation of bark beetle infestation for forest protection purposes

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ABSTRACT: Geostatistical analysis of bark beetle activity and its use for the improvement of pest control measures are presented. Data on the volume of salvage timber felling due to bark beetle infestation for the period 2002–2004 were used for the analysis. Research was carried out in the northwestern part of Slovakia. The techniques used were variogram modelling, Turning Bands Simulation and selected techniques of simulation post-processing. The maps indicating the probability that a critical volume of timber felling was exceeded in a particular location were produced. The proposed system may be used effectively for the improvement of pest control measures and development of slow the spread strategies. The benefits and shortcomings of this approach in forest protection are discussed.

Keywords: bark beetle; geostatistics; probability maps; forest protection; Slovakia

Spatial patterns in tree mortality and tree infestation by insects have been studied only scarcely (Marchetti et al. 1999; Franklin, Gregoire 1999; Otto, Schreiber 2001; Taylor, MacLean 2007), especially in the environment of declining forests (Grodzki 2005; Turčáni, Hlásny 2007). The use of geostatistics for pest control is also scarce, although it allows for a profound understanding of the distribution of spatially varying organisms. The early works by Hohn et al. (1993a,b) and Liebhold et al. (1993) presented the use of kriging techniques for the development of slow the spread strategies for gypsy moth. Recently Turčáni and Hlásny (2007) predicted the spatial distribution of four bark beetles in northwestern Slovakia using ordinary kriging.

Maps produced by the interpolation of observed data using various kriging techniques are commonly used for the description of various biological systems (Rossi et al. 1992; Legendre, Legendre 1998). While geostatistical predictions (prediction of a single value at a location) are often referred to in the biological science, geostatistical simulations (simulation of a range of values at a location) are preferentially used in the technical and environmental science – mining, air pollution, hydrology, etc. (e.g. Goovaerts 1997; Olea 1999). In this paper we emphasize the importance of the later approach to forest pest control. We analyzed bark beetle dynamics in declining spruce stands in northern Slovakia.
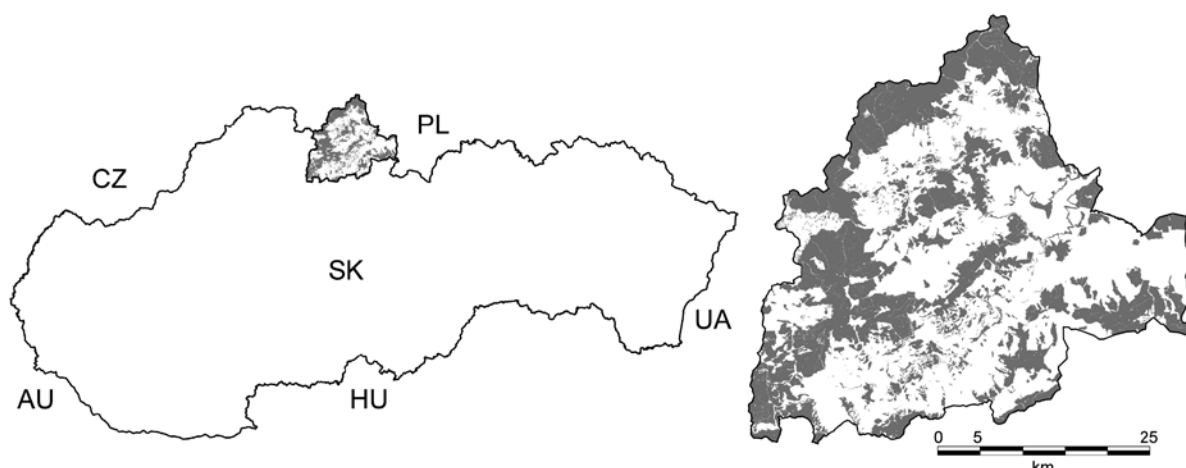
Fig. 1. Study region location and the area covered by forests

In particular, we focused on the following:
1. Geostatistical analysis of data on salvage felling due to bark beetle in the period 2002–2004.
   – Analysis of spatial variability of used data by means of variographic analysis;
   – Simulation of values in unrecorded locations (locations without any data on bark beetle infestation) in the whole region by means of Turning Bands Simulation;
   – Development of probability maps indicating the probability of exceeding a certain volume of timber felling per compartment by means of simulation post-processing tools.
2. Benefits of probability maps for bark beetle control.

Study region

Research was conducted in the Orava region in the northern part of Slovakia (Fig. 1). The size of the region is about 1,570 km^2 with 43% forest coverage. Altitudinal vegetation zones (AVZ) range from the 4th (beech) to the 8th (dwarf pine) one. Hemioligotrophic and oligotrophic sites prevailed. Moist and waterlogged sites were also frequent. European beech (*Fagus sylvatica* L.) and silver fir (*Abies alba* Mill.) dominate in the natural tree species composition (MICHALKO 1986). Norway spruce (*Picea abies* L. Karst.) naturally occupied predominantly the 7th (spruce) AVZ, and waterlogged and peaty sites at lower altitudes, as well as the parts of the 6th (fir-beech-spruce) AVZ. Nowadays, Norway spruce absolutely predominates in the region (77%) followed by European beech (11%), silver fir (5%), Scotch pine (3%) and other tree species. The region has been suffering from the extensive biotic agents-driven forest decline during the last decade. The bark beetle population has permanently been in its epidemic phase.

METHODS

Geostatistical analysis consists of a series of steps that have often been described in the literature (ISAAKS, SRIVASTAVA 1989; GOOVAERTS 1997). We described the four-step analysis in a simplified way that we used in this study. ISATIS v. 8 (Geovariances, Centre de Géostatistique in Fontainebleau) was used for all modelling.
– Positively skewed data were transformed to normal space using Gaussian Anamorphous modelling (RIVOIRARD 1994). Transformation parameters were kept to allow for the back-transformation of simulated values.
– Variogram modelling had to be done prior to simulation, because a covariance function is needed to perform a non-conditional simulation and subsequently its modification by kriging.
– Turning Bands Simulation was the core of the analysis. The idea of the method was to reduce all two- or three-dimensional simulations to the sum of several independent one-dimensional simulations. If the values of a two-dimensional function $Z(x)$ are projected on a line l, and if the values projected at the same point are averaged, it defines a one-dimensional function $Y(x_l)$. The continuity of that function along the line l is characterized by a covariance function $C_Y(h_l)$, which is directly related to the covariance of $Z(x)$, $C_Z(h)$. Then, to simulate values of $Z(x)$ with covariance $C_Z(h)$, we could just simulate values of $Y(x_l)$ on a sufficient number of lines crossing each other at the same point. To obtain a simulated value of $Z(x_1)$ at a point x_1, we projected this point on the lines and calculated the averages of the simulated values of $Y(x_l)$. Values of $Y(x_l)$ on a line were computed as weighted moving averages of pseudo-random numbers at regular intervals on that line. The
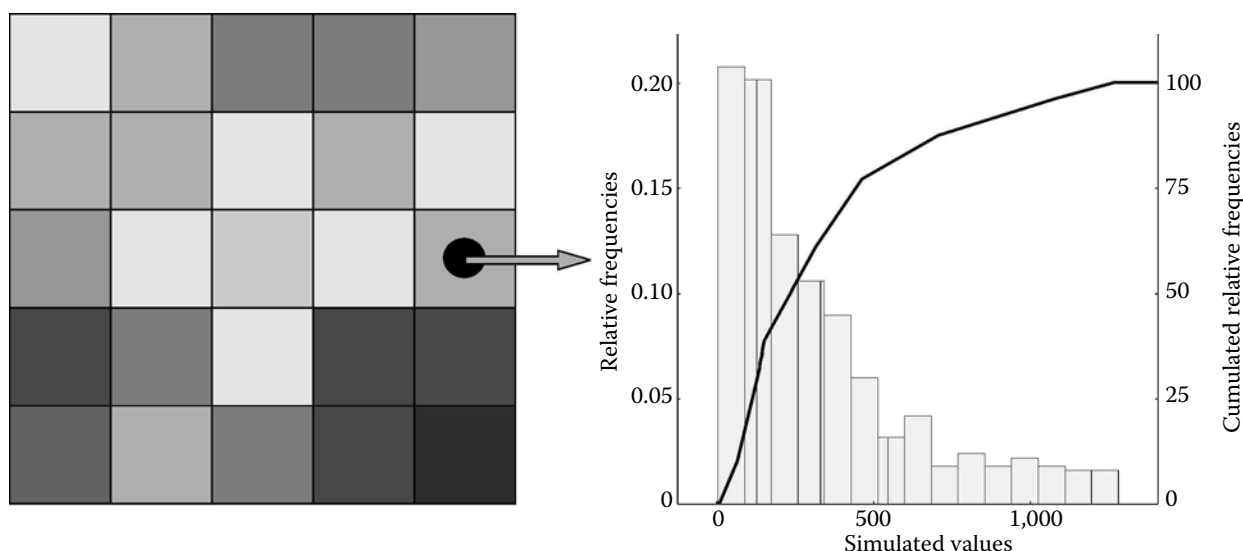
Fig. 2. Generic structure of a macro variable produced by geostatistical simulation. The distribution/cumulative distribution function is associated to each grid cell

weighting function depended on the covariance $C_\gamma(h_l)$, which had to be reproduced (DAGBERT 1981). The method is usually employed for stationary random functions but can also be used for IRF-k (CHILES, DELFINER 1999).

– A simulation technique produces a (spatial) macro variable consisting of a range of values at each grid cell. Therefore, a specific simulation post-processing is required to transform such a macro variable into a probability map. A cumulative distribution function was related to each grid cell in the macro variable (Fig. 2). Using this information, we could analyze the probabilities that a specified threshold value was exceeded in each location. Such analysis
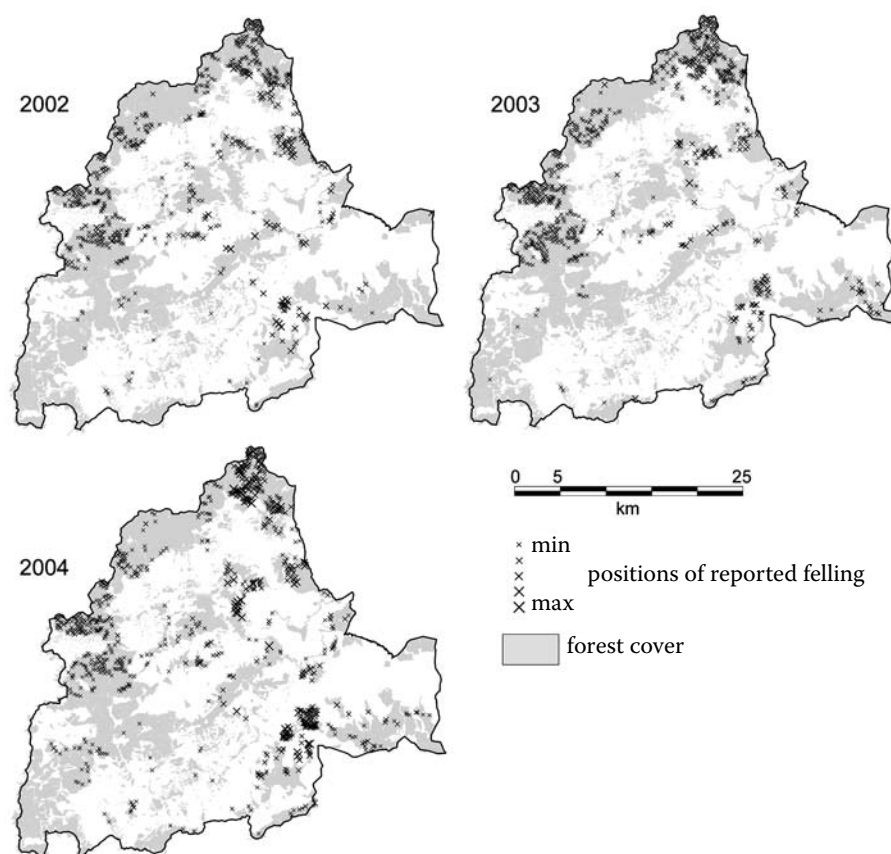

Fig. 3. Locations of reported salvage timber felling in the period 2002–2004. The data are associated to forest compartment's centre points. Cross size indicates the volume of felling

Table 1. Descriptive statistics of data on salvage felling due to bark beetle infestation in the period 2002–2004 used for the geostatistical analysis (m³)

	Average	N	Min.	Med.	Max.	25% quantile	75% quantile	Standard deviation	Range	Interquartile range	Skewness	Curtosis	Sum
2002	15.3	731	1.0	3.0	829.0	1.0	11.0	43.8	828.0	10.0	10.7	173.0	11,238.0
2003	20.5	612	1.0	3.0	559.0	2.0	14.0	51.4	558.0	12.0	5.1	35.6	12,605.0
2004	68.8	785	1.0	19.0	1,279.0	2.0	66.0	140.7	1,278.0	64.0	4.2	23.0	54,082.0

was based on the threshold of inverse cumulative distribution functions. Assigning a specified probability to each grid cell then produced probability maps.

Data

Data on salvage timber felling due to bark beetle infestation regularly reported by forest managers or owners were used for the analysis. The data is spatially referenced by forest compartments. Due to the fragmented forest cover in the region, the data were distributed rather unevenly (Fig. 3). Heavily infested areas were located preferentially at lower altitudes in the northeastern part of the region with highly fragmented forest cover. The source data distribution indicates a relatively low number of infested stands with high-infested volumes (on average hundreds of m³). On the contrary, a high number of infested stands with low volume of infested timber (on average 1–10 m³) was characteristic of the northern and northwestern parts of the region with more compact forest cover. To facilitate the geostatistical analysis, we assigned each observed volume of felling to a forest compartment's centre point. Source data statistics are given in Table 1.

RESULTS

Gaussian anamorphosis transformed values were used for the variographic analysis. Variogram models were composed of nested spherical structures with nugget effect (Fig. 4). Models for 2002 and 2003 included also the 1st order generalized covariance, which is used for modelling a zonal anisotropy in direction being perpendicular to the direction of the highest continuity. The 1st order generalized covariance model was used instead of a linear model, which could not be simulated by turning bands. The variogram parameters are given in Table 2.

Probability maps

The 300 meters resolution grid was used to produce the probability maps. Four hundred simulations with 150 turning bands were used to produce a compound variable (macro variable) containing 400 values at each grid cell (as illustrated in Fig. 2).

Subsequently we identified the zones, where the volume of felling of 20 m³ per compartment was exceeded with 70% and 90% probability (arbitrarily set thresholds to exemplify the procedure). The produced temporal series of maps is given in Fig. 5. We can see that the lower the probability, the greater part
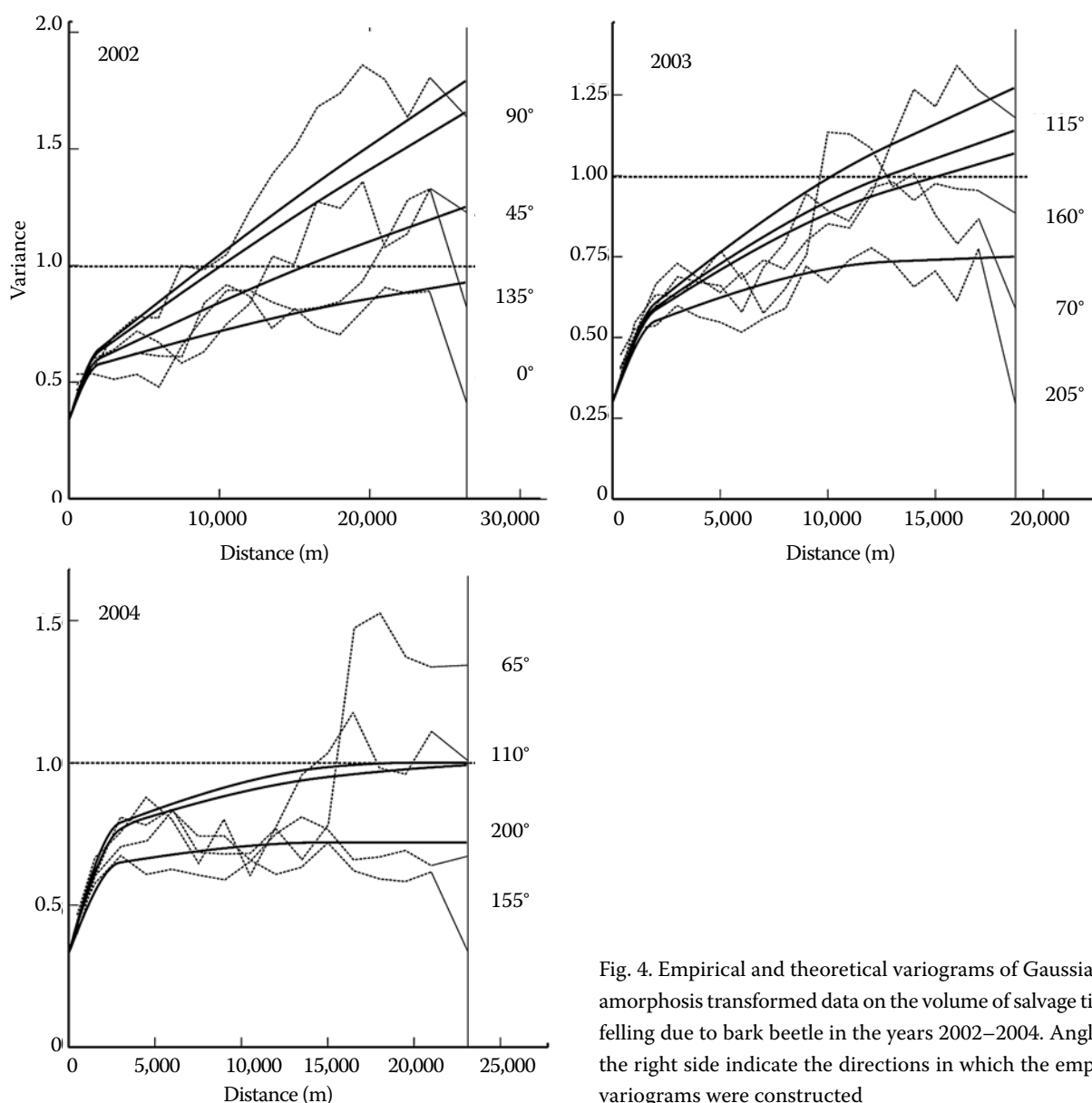
Fig. 4. Empirical and theoretical variograms of Gaussian anamorphosis transformed data on the volume of salvage timber felling due to bark beetle in the years 2002–2004. Angles on the right side indicate the directions in which the empirical variograms were constructed

of the region is indicated being above the threshold. The 90% probability stands for a very strict threshold, thus only heavily infested areas are highlighted.

A strong anisotropical pattern (prolonged in a specified direction) of infestation may be seen in the case of 2002 and 2004 dataset, corresponding to the above described variograms. The increasing extent of the above-threshold areas indicates a generally recognized progressive trend of infestation in the study region.

It should be noted that the values are simulated regardless of the actual forest cover in the region. Forest cover mask may also be applied to the probability maps to compare the identified patterns with forest stand parameters. However, such a procedure produces visually rather a fragmented pattern of infestation, which is difficult to interpret. Therefore we did not use this procedure.

DISCUSSION AND CONCLUSIONS

The paper describes a methodology allowing for the identification of bark beetle activity hot spots in a probabilistic frame. The analysis is based on the obligatory and regularly reported data, which are generally available for Forest Protection Service and forest users or owners. Thus, such models may be developed for any forest region with a functional reporting system. In this way, infestation probability maps may be continuously modelled and evaluated. Such maps allow for the optimized planning and allocation of control measures (sanitary felling and transportation of infested wood, allocation of pheromone traps and trap trees, etc.). They have a special importance in declining forests, where sanitary measures cannot be technically carried out
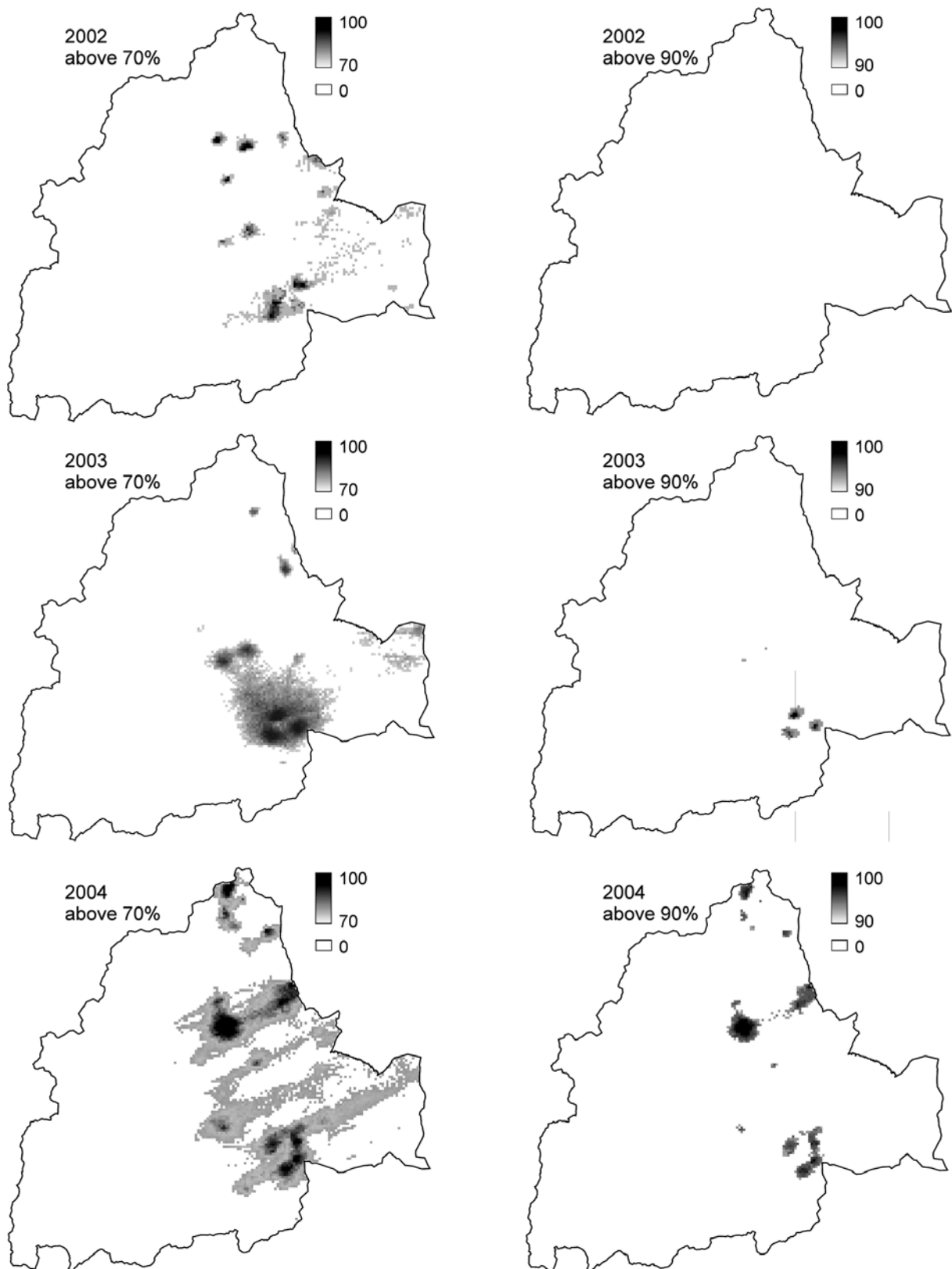
Fig. 5. Bark beetle infestation probability maps. The areas of infestation exceeding 20 m³ per compartment with 70% and 90% probability are highlighted. The maps are based on the simulation of the volume of salvage timber felling due to bark beetle outbreak by means of Turning Bands Simulation

Table 2. Parameters of the theoretical variograms constructed on the basis of salvage timber felling data due to bark beetle infestation in the years 2002–2004. Gaussian anamorphosis transformed data have been analyzed

Year	Structure	Sill	Range (scale) (m)	Anisotropy coefficients	Direction of anisotropy
2002	nugget effect	0.34	–	–	–
	spherical	0.20	2,000	isotropic	–
	spherical	0.10	20,000	isotropic	–
	1st order generalized covariance	0.90	20,000	(0, 1)	104°
2003	nugget effect	0.30	–	–	–
	spherical	0.20	2,000	isotropic	–
	spherical	0.20	13,000	isotropic	–
	1st order generalized covariance	0.90	13,000	(0, 1)	105°
2004	nugget effect	0.33	–	–	–
	spherical	0.29	3,000	isotropic	–
	spherical	0.10	3,000	(0, 1)	115°
	spherical	0.10	15,000	isotropic	–
	spherical	0.18	20,000	(0, 1)	115°

in a desired time schedule in all regions, thus their optimal allocation is crucial.

The main findings of this paper are as follows:

– Data on salvage timber felling due to bark beetle may describe effectively the spatial pattern of bark beetle infestation.
– There is a significant pattern of spatial continuity in such data that allows for its geostatistical analysis (variogram modelling, predictions, simulations, etc.).
– Conditional simulations (e.g. Turning Bands Simulation, as used in this paper) may produce reasonable and easy readable maps indicating bark beetle infestation hot spots in a probabilistic frame.

There are also several shortcomings of the proposed approach, particularly the following ones:

– Skilled staff and specialized software are needed for the particular steps of geostatistical analysis (data transformation, variogram modelling, simulation, post-processing, back-transformation, visualization…). This may hinder a broader use of the proposed system.
– Though sanitary timber felling data describes the spatial-temporal dynamics of particular disturbance agents, a range of uncertainties is associated to it. Significant improvement of the reporting system is needed to make the data fully suitable for spatial analyses.
– Practical use of the proposed system depends on a short delay between data collecting and modelling,

therefore the flow of data between foresters and data analysts should be optimized as well.

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Geoštatistická simulácia napadnutia podkôrnym hmyzom pre účely ochrany lesa

ABSTRAKT: V príspevku je prezentovaná geoštatistická analýza aktivity podkôrneho hmyzu a jej využitie pre zefektívnenie kontrolných opatrení. Analyzované boli objemy náhodných ťažieb v dôsledku podkôrneho hmyzu v období 2002–2004. Výskum bol realizovaný v severozápadnej časti Slovenska. Boli použité techniky modelovania variogramu, simulácia otáčaním pásiem a vybrané techniky na spracovanie výsledkov simulácií. Ako výsledok sme získali tzv. pravdepodobnostné mapy, indikujúce pravdepodobnosť prekročenia kritického objemu ťažby na jednotlivých lokalitách záujmového územia. Navrhnutý systém môže byť účinne využitý na zlepšenie výkonnosti kontrolných opatrení a vývoj ďalších stratégií na spomaľovanie šírenia škodcov. Na záver sú diskutované prínosy a nedostatky navrhnutého systému.

Kľúčové slová: podkôrny hmyz; geoštatistika; pravdepodobnostné mapy; ochrana lesa; Slovensko

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