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Spatial distribution of four spruce bark beetles in north-western Slovakia

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ABSTRACT: Infestation density of four the most common spruce bark beetle species was estimated on 15 study sites (10 trees per site) in the Kysuce model region in 2006. Five half-metre long sections of the stem were selected and dissected at the base of the stem; midway between the base of the stem and the base of the crown; just below the base of the crown; in the middle of the crown; and in the upper part of the crown. The infestation density of bark beetles, expressed as the number of mating chambers per dm^2, was determined. Ordinary kriging was then used to produce smooth maps and visualize spatial distribution of study species. Maps with isolines indicating high infestation were produced for study species (*I. typographus* over 0.38; *I. amitinus* over 0.15; *I. duplicatus* over 0.11; and *P. chalcographus* over 0.415 nuptial chambers per dm^2). *Ips typographus* L. remained dominant species on majority of sites having high intensity of infestation. Lower altitudes in the south-eastern part of the region were often infested by *I. duplicatus* Sahlberg and also by *I. typographus* and *Pityogenes chalcographus* L. Higher elevations in the north-eastern part of territory in the vicinity of border with Poland were heavily infested by *I. amitinus* Eichhoff (often with *I. typographus*). *P. chalcographus* was abundant on majority of territory – mainly in southern half of area. However locally, it was found in extremely high abundance. The results suggest the need for control measures set up jointly against the most abundant bark beetle species in study region.

Keywords: bark beetles; infested spruces; spatial distribution; kriging

In the last centuries, natural forests in Central Europe have been heavily converted to spruce monocultures what resulted in several million m^3 of trees infested annually by spruce bark beetles (Turčáni, Novotný 1998; Kula, Zabecki 2006). In such conditions, the pests have no barriers to spread from areas of origin to neighbouring stands. Some authors estimated that insect outbreaks would be longer and more frequent (Mattson, Haack 1987; Jankovský 2002) as a result of climate change.

The spatial distribution of bark beetles is subject of debate. It is generally agreed that pioneer bark beetles are attracted to susceptible trees by tree volatiles (primary attraction, Lindelöw et al. 1992; Tunset et al. 1993). However, on the basis of computer simulations, Byers (1996) suggested that the encounter rates between searching bark beetles and susceptible host trees are sufficiently high when beetles just travel at random, without necessarily being attracted by kairomones. Jakuš et al. (2003) suggested 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. The same authors also indicated that in the first stage of the outbreak, the beetles had migrated over fairly long distances and explored available resources.

Økland and Bjørnstad (2003) analyzed spatial synchrony of *Ips typographus* (L., 1758) in endemic situation in large areas in Norway. They found that spatial synchrony drops to regional mean after 134 km and thus, populations in close proximity were more synchronized than the regional mean. All analyses mentioned above were focused on one species and/or generally to "bark beetles", without more precise identification of their communities.

Our research area is characterized by spruce yellowing and decline, what resulted in permanent sanitary felling providing good food supply for bark beetles. Control measures were done by using sanitary felling, insecticides application and pheromone mass trapping (*I. typographus, I. duplicatus* [Sahlberg 1836] and *Pityogenes chalcographus* [Linnaeus 1761] are controlled in this way). The size of infestation is calculated on the base of the number of the infested trees, but which bark beetle species account to this amount it is not known at all. In addition, spatial distribution of populations is speculated only, what may result in low efficiency of the applied control measures.

The paper aims to give information about approximate distribution of bark beetles communities in large-scale dying spruce monocultures. The use of geostatistics helps to understand spatial distribution of selected bark beetle species. These information are worth for a more effective planning of the control measures, in order to reduce the losses due to bark beetles.

The main goals of study are to:

– Analyze infested trees growing in various sites and estimate the density and bark beetles species composition.
– Produce smooth maps which approximately identify the areas with intensity of attack (galleries per dm²) where performance of intensive control measures has to be applied.

MATERIAL AND METHODS

Field work

The infestation density of bark beetles was estimated using the modified method proposed by Grodzki (1996, 1997). In the late summer 2006, 150 infested co-dominant spruces were felled within 15 sites (10 trees per site) on study area (Figs. 1 and 2). Only the trees, which missed suitable substrate for additional bark beetles attack were evaluated (usually those with only remains of needles). Each site was large enough (about 10–20 ha with variable elevation – see Table 1) allowing finding a sufficient number of infested trees. Five half-metre long sections of each stem were selected and dissected using the following protocol: Section I, at the base of the stem (0.5–1.0 m above ground); II, midway between the base of the stem and the base of the crown; III, just below the base of the crown; IV, in the middle of the crown; V, in the upper part of the crown. The infestation density of five bark beetles, expressed as the number of mating chambers per dm², was determined. The species identification was based on galleries. We focused primarily on *I. typographus,* because of its recognized importance as a mortality-causing agent of Norway spruce stands throughout Slovakia. The presence of co-occurring bark beetles – *I. amiti-*

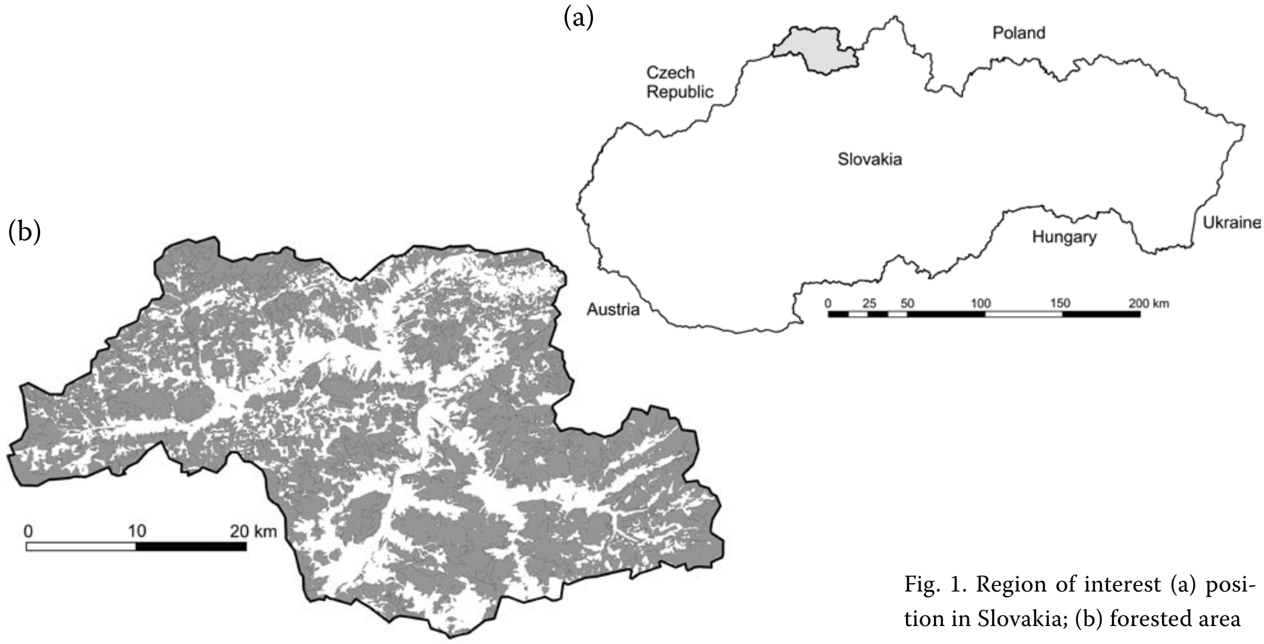

Fig. 1. Region of interest (a) position in Slovakia; (b) forested area

nus (Eichh. 1872), *I. duplicatus*, *Polygraphus polygraphus* (L. 1758), and *P. chalcographus* – was recorded as well.

Analysis of data

Many of natural systems exhibit certain pattern of spatial continuity. Spatial dependence is particularly important in an analysis of spatially varying organism distribution and environmental variables, yet many traditional statistical measures tend to ignore it (Rossi et al. 1992). As distribution of sampled populations is governed by series of endogenous and exogenous factor, the presence of this pattern can be a priori supposed. This allows us using ordinary kriging (Matheron 1963; Goovaerts 1998) to produce smooth maps of the phenomenon to show the spatial distribution of infestation density of sampled bark beetle populations. This is a linear distance-weighting based method of spatial interpolation. If we suppose the $Z(x)$ is the random process generating pest's densities at positions x, and $z(x)$ are respective densities, this is of the form:

$$Z(x_0) = \sum_{i=1}^{k}\lambda_i Z(x_i) \qquad \sum_{i=1}^{k}\lambda_i = 1$$

where: $Z(x_0)$ – estimator at site x_0 given by linear combination of random variables $Z(x_i)$ at sites x_i.

Unbiasedness condition and minimized error variance are two main features of the technique. Variogram modelling must be done prior to kriging, as it uses spatial correlation structure (variogram, covariance function) of the data to determine the weighting values. More details on this technique in the analyses of ecological data are provided by Rossi et al. (1992) and Liebhold et al. (1993). Perry et al. (2002) introduced its position in analysis of ecological data in the context of other quantitative techniques. ISATIS v. 5 provided a proper environment for all the geostatistical analyses.

To test for differences between pairs of average abundance of each species occurring in different areas the one-way ANOVA was used. Site was considered as an effect in ANOVA. Data were ln-transformed prior to analysis.

RESULTS AND DISCUSSION

I. typographus (IT), *I. amitinus* (IA), *I. duplicatus* (ID), *P. chalcographus* (PC), and *Polygraphus polygraphus* (PP) were the main species recorded during the field sampling. Locally, *Hylurgops* spp., LeConte, 1876, *Dendroctonus micans* (Kugelann 1794) and *Orthotomicus* spp., Ferrari 1867 were also found. The last five taxons were not included in the analyses.

Further, we present the results of field survey by study sites (Fig. 2). Average number of galleries per dm^2 was calculated from the 5 sampled sections.

The most abundant species on the Sadibolovci site (a – letter flags site on Fig. 2 and in Tables 1 to 3) was IT. The abundance of IT was significantly higher on this place than on places Sudovci, Kelcov and Mestsky Haj (ANOVA: F (14, 135) = 2.7463, P = 0.00133, Tukey HSD test – see Table 3). Upper part of trees was infested also by PC and IA. Abundance of IA here was significantly higher than abundance on sites Cadecka 2, Klokocov, Kelcov, Mestsky Haj which are situated in lower eleva-

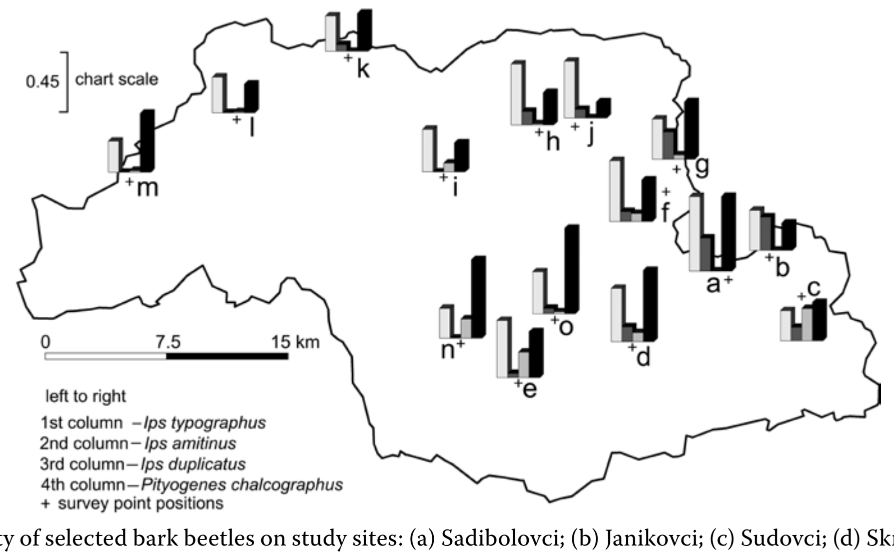

Fig. 2. Average density of selected bark beetles on study sites: (a) Sadibolovci; (b) Janikovci; (c) Sudovci; (d) Skrizelné; e) Pod Majerom; (f) Zavozy 1; (g) Zavozy 2; (h) Cadecka 1; (i) Zakopcie; (j) Cadecka 2; (k) Kubrikova; (l) Klokocov; (m) Kelcov; (n) Mestsky Haj; o) Klubina

Table 1. Basic environmental characteristics in study sites

	Elevation	Composition	Phytosanitary conditions	Diameter of sampled trees in breast height (cm)	GPS
a Sadibolovci	800–1,000	90% SP, 10% BE	declining stands	37.1	49°23'48.87"N, 19°2'42.66"E
b Janikovci	800–1,000	90% SP, 10% BE	declining stands	38.3	49°23'26.18"N, 19°3'14.59"E
c Sudovci	700–800	90% SP, 10% BE	declining stands	31.4	49°24'11.64"N, 19°5'38.89"E
d Skrizelne	700–1,000	100% SP	declining stands	37.3	49°20'16.32"N, 18°59'48.71"E
e Pod Majerom	600–800	100% SP	declining stands	36.2	49°18'52.33"N, 18°52'38.7"E
f Zavozy 1	600–700	100% SP	declining stands	43.2	49°26'13.64"N, 18°57'52.93"E
g Zavozy 2	700–900	100% SP	declining stands	35.0	49°26'32.25"N, 18°58'15.79"E
h Cadecka 1	600–800	100% SP	declining stands	44.3	49°27'40.46"N, 18°50'48.97"E
j Cadecka 2	600–800	100% SP	declining stands	42.3	49°27'12.96"N, 18°51'38.3"E
i Zakopcie	600–700	90% SP, 10% BE	local dead trees	32.8	49°24'34.35"N, 18°44'41.23"E
k Kubrikova	600–800	90% SP, 10% BE	local dead trees	33.8	49°29'43.58"N, 18°41'9.6"E
l Klokocov	600–800	90% SP, 10% BE	local dead trees	37.5	49°27'10.4"N, 18°34'33.53"E
m Kelcov	700–900	90% SP, 10% BE	local dead trees	36.7	49°25'7.44"N, 18°29'4.72"E
n Mestsky Haj	400–600	100% SP	declining stands	42.2	49°19'59.74"N, 18°47'1.66"E
o Klubina	500–700	100% SP	declining stands	31.9	49°20'30.08"N, 18°53'33.32"E

SP = spruce, BE = beech

tion (ANOVA: F (14, 135) = 2.6579, P = 0.00188, Tukey HSD test – see Table 3). Infestation by PC was extremely heavy on sections under green canopy (1.6 galleries per dm^2 on average). The Janikovci site (b) was frequently infested by IA, IT and PC were also common here. Site Sudovci is characterized by significantly lower density of IT than Sadibolovci and significantly higher density of ID than majority of other sites (ANOVA: F (14, 135) = 4.0933, P = 0.00001, Tukey HSD test – see Table 3) and PC. It seems that ID occurrence is isolated here (Fig. 3). High abundance of *P. polygraphus* here was partially caused by fact that survey trees were suppressed (infested dominant and co-dominant dead trees were quite rare in this territory). A part of trees on this site came from higher elevation, what explain presence of IA.

The most abundant species on the Skrizelne site (d) was PC (0.555). ID and IA were also present in lower abundance (Table 2, Fig. 2d). The Pod Majerom site (e) (Table 2, Fig. 2e) exhibited heavy infestation by IT (0.446). ID and PC formed efficient community and heavily infested mainly upper canopy part of dead trees. The Mestsky Haj (n) site is relatively isolated forest island, where bark beetles outbreak started later than at the majority of other sites. The infestation by IT is relatively low but PC and mainly ID (Table 2, Fig. 2n) are able effectively killing the trees in this area. These last 2 sites form main area of heigh density of ID, according to kriging results (Fig. 3).

Site Klubina (o) is on the edge of area with symptoms of spruce decline. The most important species was IT (0.325), although the most abundant species is IT (0.666) (Table 2, Fig. 2o), which reached average abundance 1.0–1.8 gallery dm^2 in upper canopy and became serious pest here. The Zavozy 1 and 2 sites (Table 2, Figs. 2f, g) are in area with presence of all 4 studied species. The most abundant was IT. ID was more abundant in lower elevation IA in higher elevation (Zavozy 2). ID was very abundant on this territory several years earlier, however it was not recorded in high abundance on surveyed trees. The sites Cadecka 1 and 2 have been heavily infested by bark beetles and fungi during the last 10 years. Currently, remaining spruce stands are continuously killed by IT mainly (Table 2, Figs. 2h, j). These stands were earlier heavily infested by ID (Turčáni et al. 2006; Zúbrik et al. 2006a). Bark beetle communities seem to be very simple and they are dominated by IT now.

The previous sites were located on the eastern part of surveyed area. The next 4 sites were selected in the western part, where symptoms of spruce decline were not visible in 2006.

The site Zakopcie is located in lower elevation, thus IA was missing and ID, PC and PP were more abundant (Table 2, Fig. 2i). Average infestation by IT is lower than in the eastern part of the territory. This pattern was also found on additional sites in the western parts. Infestation by IT reached values 0.25–0.30 gallery dm^2 (Figs. 2k, l, m) and infested trees were quite rare in this territory. ID and IA are rare here as well. PC was very abundant only in Kelcov (Fig. 2m). Not only average infestation, but also infestation of section under green canopy was lower in this region.

Spatial analyses of surveyed infestations

Despite the low number of sample data, pattern of spatial continuity could be observed for each investigated species and underlaying variograms could be constructed. This, however, hindered any directional analyses. Fig. 3 suggests that area the most heavily infested by IT is concentrated around the main valley in studied region, where spruce monocultures suffer from long-term decline. This spatial pattern agrees with pattern found on the base of felled trees (Hlásny, Turčáni, unpublished results) suggesting highly prevalence of IT in trees mortality in this region. Distribution of IA is limited to high elevations around Slovak-Polish border in the western part of study territory (elevation gradient is quite steep) suggesting its higher role in nature-closer stands in higher elevation. Smaller species (ID and PC) are distributed mainly in the southern part of territory what is surprising mainly in case of ID, because this species used to be the most abundant in the north-western part of area and it is currently distributed in local spots (probably where IT is not strong competitor). Although the maps describe clearly the main spatial trends of bark beetles distribution in the territory, the portion of uncertainty is high. This was supported by results of ANOVA when only differences on several sites were statistically significant in case of IT, IA and ID (Table 3) and there were no significant differences in case of PC (ANOVA: F (14, 135) = 1.7159, P = 0.05915). Thus, the produced maps is worth rather for scientific understanding of bark beetles spatial distribution. It may be used for practical forest protection only as preliminary information.

No environmental factor controlling observed pattern of bark beetles distribution was identified. Elevation seems to be a factor affecting the distribution of IA, but an unpublished correlations among bark beetles and series of environmental variables in model region also has not brought satisfactory results. This hinders using some supportive variables to predict bark beetles distribution over the territory by means of multivariate geostatistical techniques (kriging with external drift, co-kriging etc.) in order to reduce the uncertainty of prediction.

Table 2. Average abundance of four bark beetles on study areas (galleries per dm^2)

	I. typographus	*I. amitinus*	*I. duplicatus*	*P. chalcographus*
a Sadibolovci	0.581	0.257	0.000	0.580
b Janikovci	0.297	0.236	0.000	0.234
c Sudovci	0.234	0.105	0.251	0.299
d Skrizelne	0.416	0.117	0.071	0.555
e Pod Majerom	0.446	0.033	0.199	0.359
f Zavozy 1	0.473	0.078	0.061	0.323
g Zavozy 2	0.312	0.211	0.033	0.446
h Cadecka 1	0.440	0.067	0.000	0.123
j Cadecka 2	0.331	0.000	0.069	0.226
i Zakopcie	0.474	0.106	0.009	0.252
k Kubrikova	0.275	0.052	0.000	0.298
l Klokocov	0.275	0.000	0.007	0.221
m Kelcov	0.241	0.000	0.013	0.459
n Mestsky Haj	0.232	0.000	0.147	0.612
o Klubina	0.325	0.042	0.016	0.666

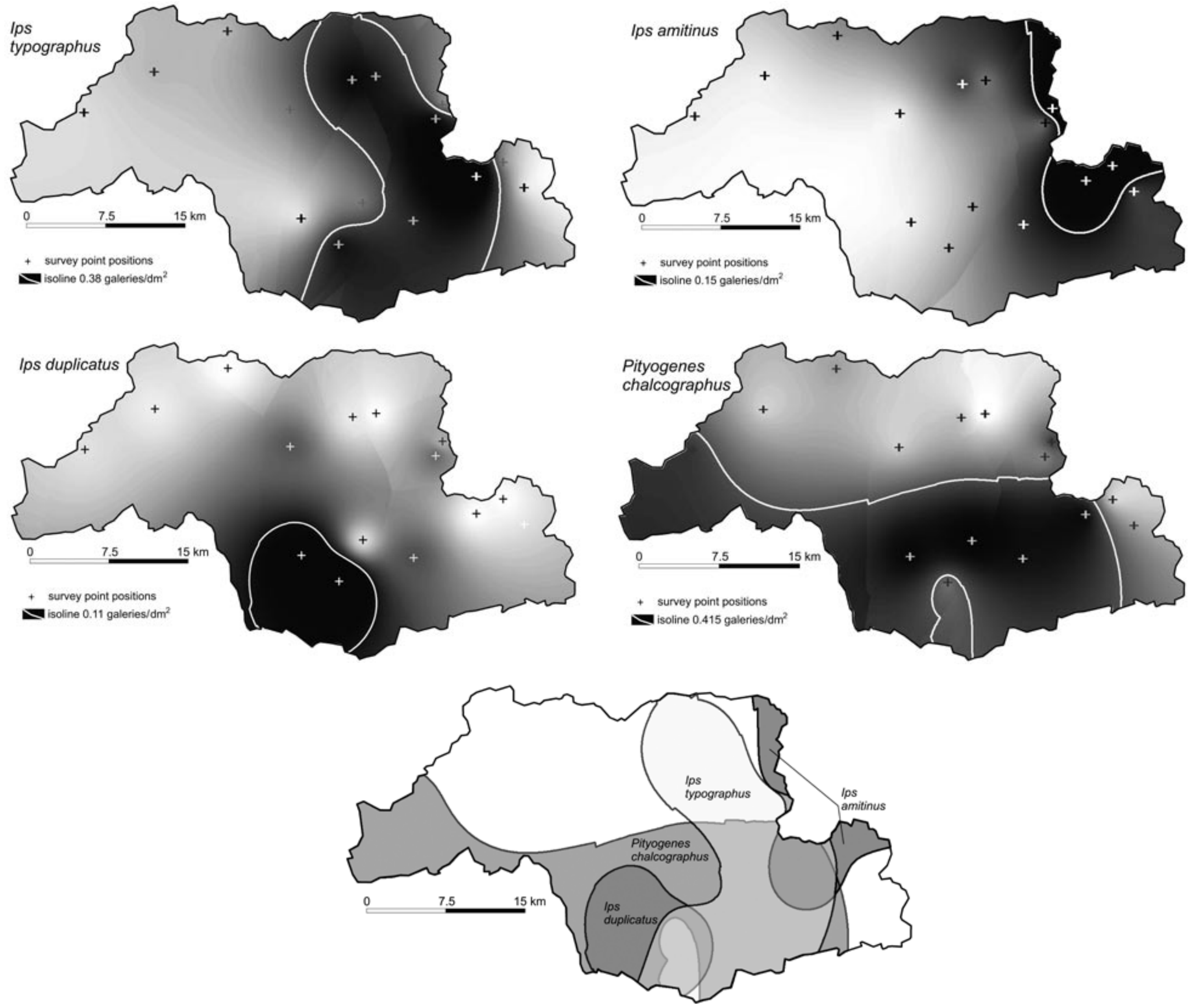

Fig. 3. Synthesis of bark beetles survey by using kriging (isolines of infestation were based separately to each species on the base of its size, on the part of tree which it attacks and its importance in forest protection)

To visualize the result, selected isoline was drawn on each map to delimit the areas exhibiting the highest density of individual bark beetle species (Fig. 3). A general threshold could not be set as the infestations of investigated species were incomparable – due to the different niche which they occupied along the tree.

Table 3. The results of ANOVA post-hoc comparison (average abundance of *I. typographus*, *I. amitinus* and *I. duplicatus*) on individual study sites

		(c)	(e)	(f)	(g)	(h)	(j)	(i)	(k)	(l)	(m)	(o)
I. typographus												
1	a	0.012379									0.016771	0.011377
I. amitinus												
1	a						0.046171			0.046171	0.046171	0.046171
I. duplicatus												
1	a	0.00059	0.02590									
2	b		0.02590									
3	c			0.04584	0.00754		0.07063	0.00131	0.00059	0.00108	0.00178	0.00213
5	e					0.02590		0.04707	0.02590	0.04078		

The paper presents an information which is highly needed from the point of forest protection, because if control measures are applied against single species, other species may increase density and may become the primary pests. Until now, the territory of Kysuce was categorized only at the base of amount/intensity of trees felled in previous season. Those data did not give any suggestions about species, which are responsible for tree mortality. For example, the data we analyzed showed the north-eastern area close to Polish border is heavily attacked by IA. However, trap trees were not prepared here, because survey and control are done by both felling infested trees and pheromone traps. Previously, it was not known that IA is very abundant at those areas at all. Information about spatial distribution of bark beetles may suggest where to apply control measures against synergic attack of several bark beetles species. This brings possibility to improve efficiency of control measures and reduce time and costs. In spite study lasted only a year, the analyse of IT time series suggested, that population growth of bark beetles was not stochastic (unpublished autocorrelation function = ACF and partial autocorrelation function = PACF results) and thus presented the spatial pattern may be stable longer time. To compare spatial distribution of some bark beetles, it may be useful to analyze captures to pheromone traps as it was done in the Tatras Mts. by Zúbrik et al. (2006b). On the other hand, captures to pheromone traps give information influenced by migration of beetles.

CONCLUSIONS

I. typographus remained dominant species on the majority of sites having high intensity of tree infestation mainly along the main valley in the region. Lower elevations occurring in the southern part of region were often infested by *I. duplicatus* with *I. typographus* and *P. chalcographus*. Higher elevations close to Polish border were heavily infested by *I. amitinus* (as dominant or accessory species of *I. typographus*). *P. chalcographus* was common on the whole sampled territory – mainly in the southern half of the region. It was found in extremely high abundance locally.

The results suggest that it is necessary to plan the control measures always jointly for several the most abundant species: *I. amitinus*, *I. typographus*, and *P. chalcographus* in higher elevations and/or *I. typographus*, *I. duplicatus*, and *P. chalcographus* in lower elevations.

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Prostorová distribuce čtyř druhů kůrovců na severozápadním Slovensku

ABSTRAKT: V roce 2006 jsme na 15 studijních lokalitách (10 stromů na každé lokalitě) studovali napadení čtyřmi druhy kůrovců. Na každém stromu bylo zvoleno pět sekcí, které jsme analyzovali: báze kmene; střed mezi bází a začátkem koruny; začátek koruny; střed koruny; horní část koruny. Na všech analyzovaných sekcích byla determinována intenzita napadení vyjádřená počtem mateřských komůrek na dm^2. Na vizualizaci dat byl využit klasický kriging, pomocí kterého se připravily mapy průměrných hodnot intenzity napadení pro čtyři nejvýznamnější druhy. Pro ně se připravily mapy s izoliniemi, znázorňující silné napadení (*I. typographus* více než 0,38; *I. amitinus* přes 0,15; *I. duplicatus* více než 0,11 a *P. chalcographus* přes 0,415 mateřské komůrky na dm^2). Podle výsledků je lýkožrout smrkový (*Ips typographus* L.) dominantní druh na většině lokalit, kde většinou dosahuje vysoké intenzity napadení. Nižší nadmořské výšky na jihovýchodě území byly často intenzivně napadeny lýkožroutem severským (*I. duplicatus* Sahlberg) spolu s lýkožroutem smrkovým a lýkožroutem lesklým (*Pityogenes chalcographus* L.). Vyšší nadmořské výšky na severovýchodě území v blízkosti polských hranic byly silně napadeny lýkožroutem menším (*I. amitinus* Eichhoff) – často spolu s lýkožroutem smrkovým. Lýkožrout lesklý byl četný na většině území – hlavně v jižní polovině. Jenom lokálně dosahoval extrémních četností. Výsledky naznačují, že obranná opatření proti kůrovcům musejí být uplatňována komplexně a současně proti několika druhům kůrovců na stejném místě.

Klíčová slova: kůrovci; napadené smrky; prostorová distribuce; kriging

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