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The relationship between potential solar radiation and spruce bark beetle catches in pheromone traps

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Abstract. We analysed the relationship between the amount of potential solar radiation and spruce bark beetle *Ips typographus* (L.) catches in pheromone traps in an unmanaged nature reserve in the Carpathians (middle Slovakia region), from 2006 through 2009. This relationship was analysed under outbreak conditions. The number of traps varied in different years from 70 to 92. The traps were installed in spruce-forest-dominated stands affected by a windstorm in 2004. A GPS device was used to mark the position of the pheromone traps. The potential solar radiation was calculated with GIS tools for three different time periods in each year: with entire year, for main flight season of the spruce bark beetle and the spring swarming period. The relationship between the amount of potential solar radiation and the spruce bark beetle catches was statistically significant for each year and each time period except for the spring swarming in 2007, when the pheromone traps were not set up on time.
Keywords Spruce bark beetle, pheromone trap, solar radiation, nature reserve, disturbance.

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Introduction

The spruce bark beetle *Ips typographus* (L.) may be recognised as the most important forest pest in Europe during the second half of the 20th century. Usually a disturbance of the forest environment is needed to trigger a population increase. In most cases, the disturbance is caused by wind, a long-lasting drought or the co-occurrence of high temperatures and a dry period (Sauvard 2004). A population generally decreases after consuming all substrate suitable for reproduction (Sauvard 2004) or due to the effects of a long wet and cold period (Grodzki et al. 2006).

The effect of insolation on spruce bark beetles attacks has long been known (Fekete 1876), but no previous research has been conducted to define this dependence quantitatively. In particular, no previous research has investigated the effect of insolation on the catches of spruce bark beetles in pheromone traps. Sunlight, consequent heat accumulation and resulting temperature of the environment have direct effects on spruce bark beetle development, swarming and flight activity (Netherer & Pennerstorfer 2001, Pfeffer 1955). Schopf & Köhler (1995) found that insolation has an important influence on the attacks on trees by bark beetles and that insolation also affects the tendency of spruce bark beetle infestations to spread. Insolation primarily affects trees in proximity to windthrows. These trees are exposed to sudden illumination and are stressed by the increased direct solar radiation. They show decreased resistance against bark beetles. After the death and the defoliation or cutting of the attacked trees nearest the windthrow area, new trees are exposed to direct sunlight at the newly formed stand edge. The effect of this mechanism is that the most attractive areas for attack are sun exposed stand edges (Anonymous 1877, Schopf & Köhler 1995). The difference in temperature and thermal sum arising between the values of the phloem and the air depends on weather and on exposure (Annila 1969). Higher temperatures on the sunlit part of the stem can also increase the release rate of primary attractants into the air (Baier & Bader 1997), and insolation also affects the release of terpenes and pheromones into the air (Zumr 1985). Solar radiation can have additional indirect effects on bark beetle populations. The annual patterns of mean temperature are related to solar radiation patterns, which vary with latitude. At the landscape and local scales, temperature patterns are influenced by variations in insolation and microsite factors. Furthermore, variations in elevation and orientation (i.e., slope and aspect) affect the amount of solar radiation received at different locations (Dubayah & Rich 1995, Huang & Fu 2009). Various types of studies require data on solar radiation, but such data are not available because this variable is not frequently measured. Geographic information systems (GIS) offer an attractive solution to the calculation of potential solar radiation (Dubayah & Rich 1995). Potential solar radiation is relevant to areas unobstructed by the surrounding forest canopy. The potential solar radiation was previously estimated also in the PHENIPS (Baier et al. 2007) and TANABBO model (Jakuš et al. 2005). In these models, however, solar radiation acts as only one of the input variables.

Our working hypothesis is that insolation, consequent heat accumulation and temperature of the environment affect both the activity of spruce bark beetles and the release of pheromones and primary attractants and that there exists relationship between insolation and bark beetle catches in pheromone traps. The aim of this study is to reveal and quantify the relationship between the amount of potential solar radiation and spruce bark beetle catches in pheromone traps.

Materials and methods

Site description

Spruce bark beetle populations were monitored in the Nature Reserve (NR) Fabova hoľa from 2006 through 2009. The NR Fabova hoľa is situated in Western Carpathians (Central Slovakia, summit coordinates: N 48°46.346”, E 19°53.149”) in Slovak Ore Mountains and is part of the Muránska planina National Park. The altitudinal range of the NR is 1100–1440 m asl. The NR has an area of 260 ha, with forest cover representing more than 250 ha of the total. The dominant tree species is Norway spruce (*Picea abies* [L.] Karst.), with a total cover of 100%. Fabova hoľa was affected by wind disturbances in 2004 and 2007. The total volume of the windthrown trees in both cases was approximately 7,500 m^3, and the age of the windthrown stands was approximately 150 years. Our research was conducted on a plot attacked during 2004. Barriers of pheromone traps were installed in this plot, and sanitation felling was conducted in the vicinity of the nature reserve.

The volume of wind-felled trees in 2004 in the forest stands from which our data have been assembled was approximately 2,100 m^3, and the area of the windthrow was approximately 4.3 ha. Another 1,500 m^3 of wind-felled trees, covering 2.9 ha, were in the adjacent stand. The wind event in 2007 left an additional 400 m^3 of wind-felled trees in the study stands. The volume of trees attacked by the spruce bark beetle from 2006 through 2009 in our study stands reached 3,000 m^3, and the volume attacked in the adjacent stand reached 1,900 m^3. A more detailed description of Fabova hoľa NR and of the history of the wind disturbance was presented by Mezei et al. (2011).

Data collection

The data for the study were collected from Ecotrap (omnidirectional cross type, Fytofarm Ltd., Bratislava, Slovakia) and Theysohn (in 2006) (Theysohn, Salzgitter, Germany) pheromone traps installed in the form of barriers (Jakuš 1998a). The traps were installed by the National Park administration, primarily as a management tool to prevent the possible effects of bark beetle outbreaks on the surrounding stands. The Ecotrap traps were provided with a selective sieve to prevent the capture of larger insect species. Two types of pheromone lures for spruce bark beetle were used: IT Ecolure Extra in 2006–2008 (Fytofarm Ltd., Bratislava Slovakia) and Pheroprax A (Basfag, Ludwigshafen, Germany) in 2009. These two pheromone lures can be considered comparable, and the Theysohn and Ecotrap pheromone traps can also be considered comparable (Novotný et al. 2003). The pheromone traps were installed on slopes oriented to the S, SW, W, and NW. The distance from the pheromone traps to the nearest healthy spruce tree did not fall under 10 m, and the active surface was situated 1.5–2 m from the ground in agreement with the Slovak national norm for pest protection. The traps were checked every 7–14 days, and the beetle catches were removed from the traps and counted when the traps were checked. The catches were evaluated separately for each year. Each pheromone trap was evaluated separately. Pheromone traps that were damaged during the monitoring period were excluded from data processing. The numbers of pheromone traps for different years were as follows: 2006 – 70, 2007 – 92, 2008 – 85, 2009 – 83. A bark beetle population curve was calculated for each year based on the mean catches calculated from all traps after each time at which the traps were checked. These curves were used to identify the periods when the bark beetle population was active as well as the periods of spring swarming.

Calculation of solar radiation and statistics

The solar radiation was calculated with a digital elevation model (DEM) created for this purpose with ArcView 3.2 (Esri, Redlands, USA) software. The position of each pheromone trap was located with a GPS device. The values of potential solar radiation (W h m^{-2}) were assigned to the corresponding traps with ArcMap 9.3 software (Spatial Analyst – Points Solar Radiation)(Esri, Redlands, USA). The calculation of solar radiation in an ArcGis (Esri, Redlands, USA) environment is described in more detail by Huang & Fu (2009).

The amount of potential solar radiation was calculated separately for three different periods of each year. We calculated the amount of solar radiation over the whole year (Figure 2), over the period during which the population of the spruce bark beetle in Fabova hoľa was active (Figure 3), and over the period of spring swarming (Figure 4). The last two periods were identified from the bark beetle population curve created on the basis of the pheromone trap catches.

The data obtained were analysed with simple linear regression in STATISTICA 7.0 software (StatSoft Inc., Tulsa, USA). Log-transformed data were used for the calculations.

Results

Data from pheromone traps

The monitoring of the spruce bark beetle at Fabova hoľa nature reserve was performed on a population that had reached epidemic levels. The monitoring began in 2006, the second year after the primary disturbance. The developmental pattern of the bark beetle population in individual years is illustrated in Figure 1. In 2006, two years after the disturbance, the population was exhibiting relatively low catches in pheromone traps. In 2007, the

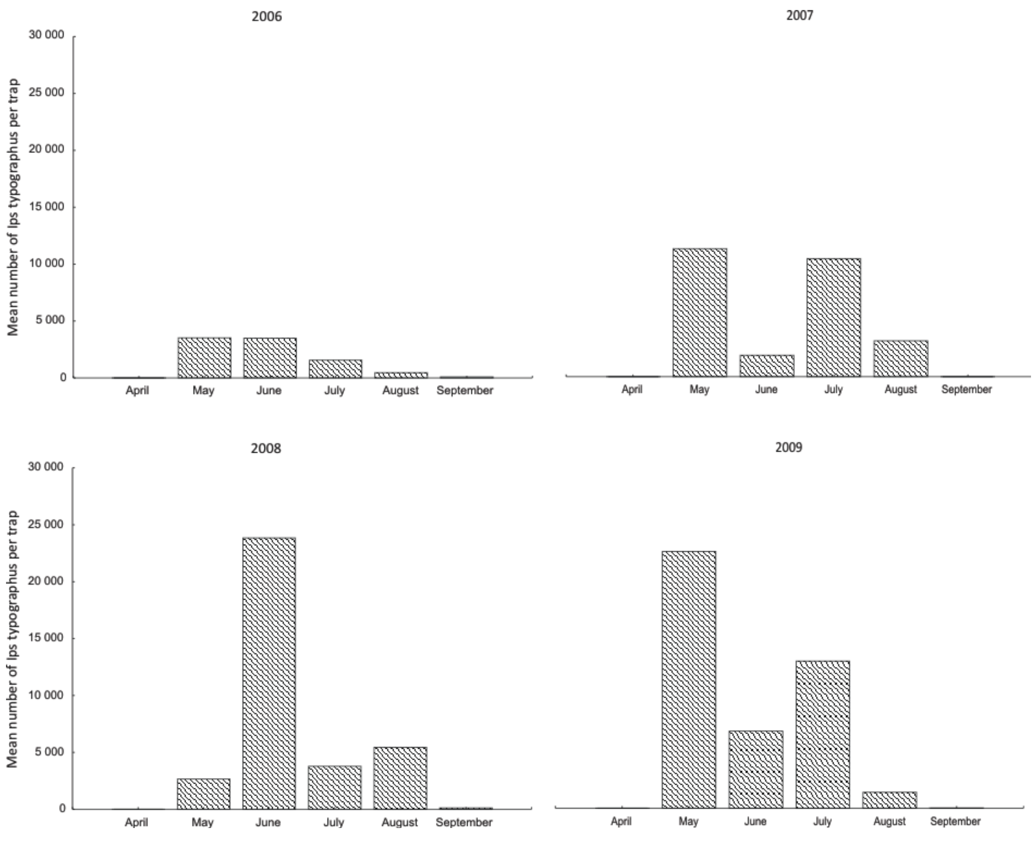

Figure 1 The developmental course of the bark beetle population in 2006–2009 in Fabova hoľa Nature Reserve (catches of spruce bark beetle individuals per trap)

mean catches of spruce bark beetle individuals per trap increased conspicuously, due in part to the occurrence of the second generation in the summer. In 2008, the time at which the first generation of the bark beetle was observed was later than in 2007. However, the average number of individuals captured was more than double that of the preceding year. The start of the second generation is recognisable towards the end of summer 2008. The development of swarming was similar in 2009 and 2007, but the catches of spruce bark beetles were much higher in 2009.

Solar radiation and bark beetle catches

The results of the regression analysis show the relationship of the spruce bark beetle catches in the pheromone traps to the amount of solar radiation. These results are summarised in Table 1.

The numbers of pheromone traps differ over the years because the pheromone trap barrier was installed as a management measure to prevent the spread of spruce bark beetles into the surrounding stands. However, the position of the barriers and the positioning of most of the pheromone traps remained essentially unchanged.

The results presented in Table 1 and Figures 2–4 confirmed that a relationship exists between the amount of solar radiation and the spruce bark beetle catches in pheromone traps. The only exception was the spring swarming in 2007, when the pheromone traps were not installed before the first swarming period. The relationship was the strongest over the whole year period when the maximum r^2 reached 0.36 (in 2008), and for the main flight season of the spruce bark beetle when the maximum r^2 reached 0.33 (in 2008). In the period of spring swarming the maximum r^2 was 0.19 (in 2006) (Table 1). In general, the relationship between spruce bark beetle catches and solar radiation was the weakest for the spring swarming period and low values of the coefficient of determination suggest that solar radiation is a weak predictor for bark beetle catches, however significant in most of the presented cases.

Discussion

The amount of potential solar radiation calculated in the GIS environment represents the amount of solar radiation on an open plot in the absence of any influence by the forest stand or by clouds. Baier et al. (2007) suggest that data of this type may be applicable to windthrows or to south-facing stand edges because the stand edges are subject to bark beetle invasions more frequently than are stand interiors (Schroeder & Lindelöv 2002). Such localities were selected for the installation of pheromone traps in the study area. This forestry practice is standard in Slovakia. According to Hedgren et al. (2003), trees at stand edges show a higher risk of attack by bark beetles for two principal reasons. Large quantities of host volatiles are released from fresh stumps and logging waste (or, in our study, non-removed windthrown trees), and spruce bark beetles prefer to colonise sun-

Table 1 Results of linear regression analysis of potential solar radiation and spruce bark beetle catches in pheromone traps during selected periods

	over the year			active season			spring swarming		
Year	n	r^2	p	n	r^2	p	n	r^2	p
2006	70	0.27	< 0.0001	70	0.27	< 0.0001	71	0.19	0.0001
2007	92	0.14	0.0002	91	0.19	< 0.0001	96	0.00	0.6515
2008	85	0.36	< 0.0001	85	0.33	< 0.0001	83	0.11	0.0014
2009	83	0.14	0.0004	83	0.16	0.0002	81	0.07	0.0140

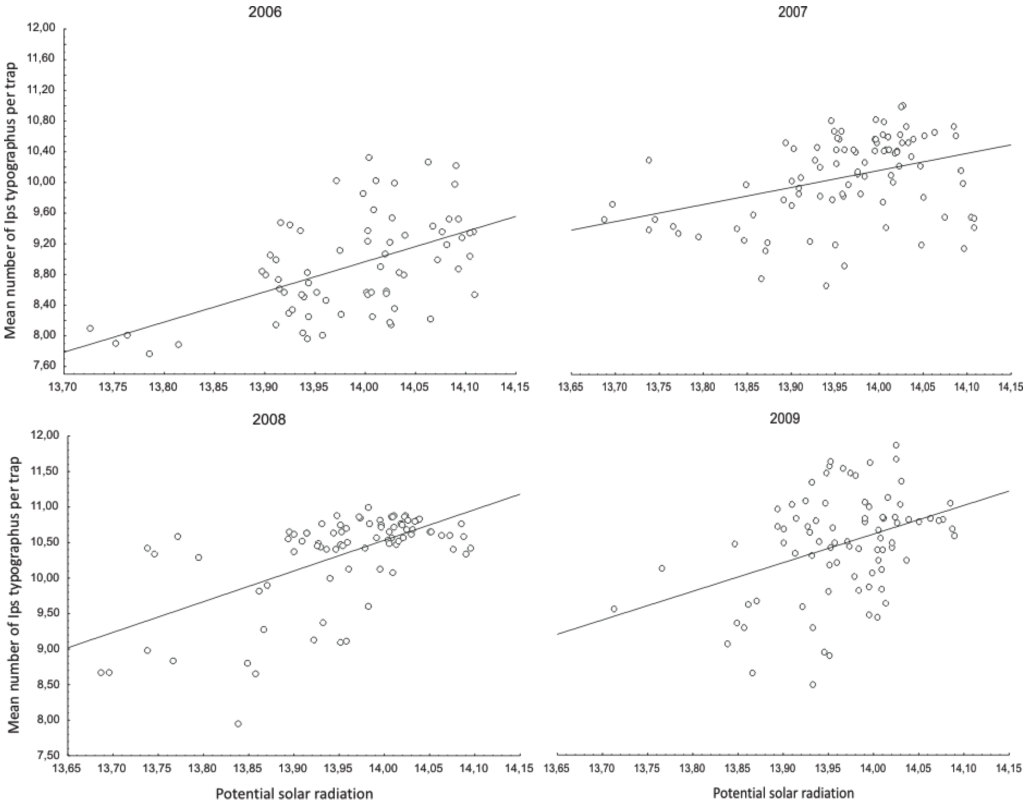

Figure 2 Scatterplot of the solar radiation calculated for entire year and the log-transformed spruce bark beetle catches in 2006–2009

exposed trees. Although the temperature of logs on the shady side can be lower by 20 – 30 °C than on sun exposed sides, the temperature of the phloem follows the curve of direct sunshine rather than that of the air temperature. This relationship between phloem temperature and sunshine is the strongest in summer month and the difference between thermal sums in the air and in the phloem also depends on exposure to sunshine (Annila 1969). These facts stress the importance of insolation in relation to bark beetle population development because this is related to temperature (Wermelinger & Seifert 1998).

In our study, we used three periods of the year to investigate the relationship between the potential solar radiation and the spruce bark beetle catches in the pheromone traps. We found that this relationship was stronger over the whole year and for the main flight season of the spruce bark beetle than for the spring swarming period. We might expect that this relationship would be the strongest in the spring because of the importance of temperature as a limiting factor for beetle flight, but we assume that a weak relationship between the potential solar radiation and the spruce bark beetle catches at the spring swarming period could be caused by windbreaks and windfalls that occurred following the autumn and winter. Both windthrow events in Fabova hoľa occurred during periods when the bark beetles

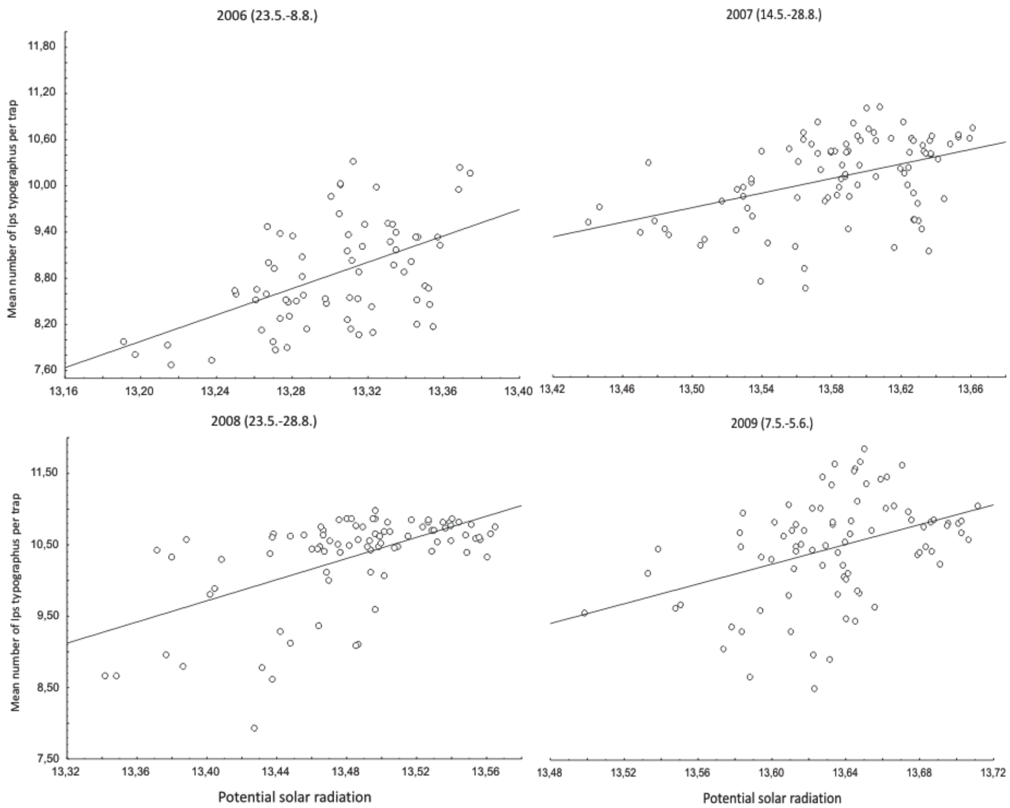

Figure 3 Scatterplot of log-transformed solar radiation calculated for the main flight season of the spruce bark beetle and log-transformed spruce bark beetle catches in 2006-2009

were not active, in November and August. This substrate could be more attractive to the bark beetles than the pheromone traps themselves.

We did not find any relationship between the potential solar radiation and the spring catches in 2007, when the traps were not set up on time. Note that we also analysed the period corresponding to the entire year. Even if the bark beetles are not active during the winter, early spring and late autumn, an analysis of the entire year could be useful in cases when no data are available about the populations of bark beetles from an area and we want to prepare a map of susceptibility or a proposed set of pheromone trap locations to obtain the best possible trap performance. The pheromone traps in Fabova hoľa were installed on slopes with S, SW, W and NW orientations. However, Jurc et al. (2006) conducted research on a karst plateau in Slovenia over an altitudinal range of 440–750 m asl and identified a strong correlation between the population density of the spruce bark beetle and NE exposure. Akkuzu et al. (2009) conducted research in Turkey and caught more spruce bark beetles in pheromone traps situated at higher altitudes (1700–2200 m asl), on slopes with a southerly aspect. However, at lower-altitude sites (1100 – 1700 m asl), more individuals were trapped on slopes with a northerly aspect. According to Zumr (1985), spruce bark beetle attacks at lower elevations are focused on valleys and on the low-

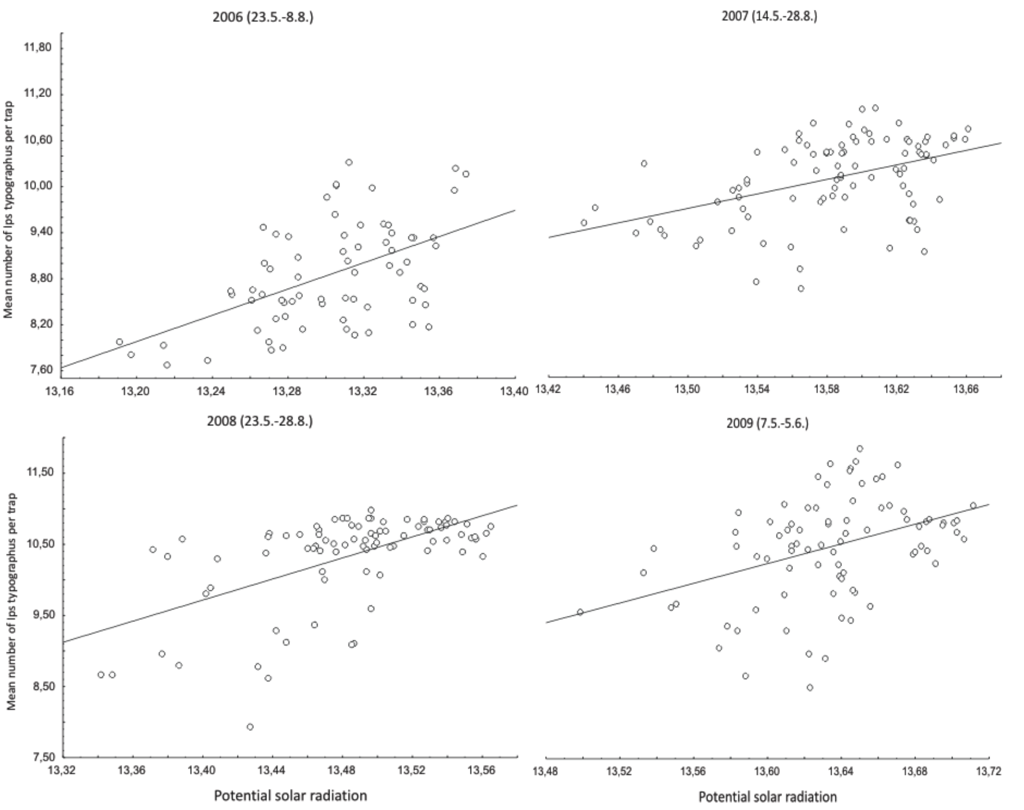

Figure 4 Scatterplot of log-transformed solar radiation calculated for the spring swarming period and log-transformed spruce bark beetle catches in 2006-2009

est parts of the slopes, whereas the attacks at higher elevations are focused on trees at forest edges in sunlit areas. Schopf & Köhler (1995) conducted a study of spruce bark beetles in a forest in Bavaria. Based on their study, they stated that insolation is the driving factor that affects the spread of infestation in spruce bark beetle outbreaks. Jakuš (1998b), investigating the occurrence of bark beetles under endemic population conditions in a natural mountain forest, also found that the distribution of bark beetles on spruce windthrows and windbreaks is influenced primarily by the host geometry and by insolation, whereas the species *Ips typographus* was affected primarily by insolation and secondarily by the condition of the host. Similarly, Jakuš (1998c) found that the proportion of stems attacked by *Ips typographus* was larger for windthrown stems having less contact with soil and more exposure to solar radiation. Research on the propagation of *Ips typographus* outbreak in the High Tatras Mts. has also identified the importance of solar radiation (Jakuš et al. 2003). Solar radiation and the gradation phase were the principal factors driving the outbreak of the spruce bark beetle. The spread of bark beetle spots in a northwards direction is a proof of the importance of solar radiation. There was practically no propagation southwards (i.e., to north-facing stand edges). The most rapid propagation was also observed to proceed northwards in the Bavarian forest (Schopf & Köhler 1995). The amount of wood attacked per hectare in the Tatra Mts. was characteristically greatest on west-facing and southeast-facing slopes, which generally provided the most favourable conditions for *Ips typographus* development (Grodzki et al. 2006). Jakuš et al. (2011) conducted a study in the Šumava Mts. and compared the surviving trees with the dead trees resulting from a spruce bark beetle attack. This study showed that the trees whose stems were better protected from direct solar radiation by their own branches exhibited higher resistance against spruce bark beetle attacks. In contrast, Lausch et al. (2011) analysed an 18 year time series of data but identified no single factor influencing the distribution of the *Ips typographus* population in the Bavarian forest. They found that the influence of solar radiation was only minor. However, these authors did not analyse the impact of solar radiation at stand edges, as did, for example, Schopf & Köhler (1995) and Jakuš et al. (2003).

Conclusions

Solar radiation influences bark beetle catches in pheromone traps. We found that the relationship between the amount of potential solar radiation and spruce bark beetle catches does not depend on the outbreak phase, i.e., solar radiation is a factor affecting spruce bark beetle catches over the entire flight season. Moreover, potential solar radiation can be determined, at least approximately, with the aid of GIS methods. Consequently, it can serve to support decision making about the application of pheromone traps.

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