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ORIGINAL RESEARCH ARTICLE

Impact of selected stand characteristics on the occurrence of the bark beetle *Ips typographus* (L.) in the Beskid Żywiecki Mountains

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Abstract. Recently, Norway spruce stands in Beskid Żywiecki (Western Carpathians) have been plagued by bark beetle outbreak affecting an extensive area over a large range of altitudes. Georeferenced data (2356 records) from 2009–2011 of the volume of felled spruces showing insect infestation in forest sub-compartments were analysed with respect to selected site and stand characteristics. The infestation intensity varied between individual parts of the examined area. Spruce mortality, recorded evenly across all slope expositions, was higher in the zones 800 m – 1000 m and above 1000 m than in the zone below 800 m. The infestation intensity increased slightly with spruce representation in the stands and was higher in stands older than 80 years. There was no clear correlation between spruce mortality and site quality. However, in areas with more diverse and fertile sites mortality was lower. In overall, the results obtained in this study are in line with previous knowledge on the subject, but patterns describing bark beetle preferences in infested areas appear to be less pronounced than those found in earlier publications. Risk assessment and current planning of forest protection measures in stands affected by bark beetle outbreaks should be based on the here described characteristics of spruce susceptibility to insect infection.

Key words: insect outbreak, site, stand characteristics, spatial analysis, *Picea abies*

1. Introduction

Bark beetle *Ips typographus* (L.) is the most dangerous insect feeding on spruce cambium, which often tends to occur in mass outbreaks that would result in dieback of entire stands. Gradations last sometimes for many years, covering vast areas. In Poland, they were observed as early as in the eighteenth century, both in the south and the north of the country (Capecki 1986; Michalski 1998; Michalski et al. 2004; Grodzki, Michalski 2013).

In the last decade of the twentieth century, Norway spruce stands in the Beskid Żywiecki were still considered, in contrast to the forests of the Silesian Beskid, healthy, resistant and free of *Armillaria* disease (Capecki 1994). Since 2002, both in the Silesian and Żywiecki Beskids, the outbreak of bark beetles has developed dynamically, which initially affected spruce stands growing at low altitudes (Grodzki 2004). This process has gradually spread to higher positions to the top of the mountains, with a steady increase in extent and intensity. The main factor contributing to the outbreak in this area is susceptibility of spruce suffering from *Armillaria* disease (Grodzki 2007a, 2009a) whose symptoms have been observed in large areas of the Beskid Żywiecki (Lech, Żółciak 2006). During the culmination phase – in 2007–2008 (Szabla 2013) – it was observed that in case of high population and favourable weather conditions, bark beetle also attacked spruce at higher altitudes (Grodzki 2009b, 2010).

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Bark beetle outbreaks always depend on two elements: the status of its population and the resistance/susceptibility of trees (Christiansen et al. 1987). The state of bark beetle population, apart from its size, results from sex structure (Lobinger 1996), reproduction rate and degree of destruction by its natural enemies, which determine the dynamics of its numbers. The susceptibility of spruce to bark beetle attack depends on, inter alia, age, share of spruce, location (altitude and exposition), habitat conditions and physiological state and health of trees, mainly related to hydrothermal conditions (Nef 1994; Jakuš 1995; Dutilleul et al. 2000; Netherer, Nopp-Mayr 2005; Grodzki 2007a, 2007b).

Netherer and Nopp-Mayr (2005), based on multifactorial analysis of selected characteristics of forest stands growing in the protected areas, proposed a relatively simple system of stand vulnerability assessment known as Predisposition Assessment System. In the Polish mountains, significance of some of these characteristics as sources of variation in relation to data on catches of bark beetles to pheromone traps (Grodzki 2007b) was confirmed, and – to some extent – through the spatial analysis of tree mortality due to infestation by cambiophagous insects, both in protected forests (Grodzki et al. 2006) and the managed ones (Grodzki 2009b).

The aim of this study was to evaluate the effect of selected characteristics describing habitats and stands on the intensity of tree mortality in the final phase of bark beetle outbreak in the spruce forests of the Beskid Żywiecki, using analysis of spatial data. It seems that, given the availability of data from the Spatial Information System of State Forests (databases and digital maps) describing the terrain and the characteristics of forests, it would be possible to use it to predict the threat of bark beetle outbreak.

2. Study area and methods

The analyses presented in this paper were carried out using data on the mortality of spruces infested by bark beetles in the years 2009–2011 in the stands within the area of the Beskid Żywiecki in two forest districts: Jeleśnia and Ujsoły. Located between them, the stands of Węgierska Górka Forest District were omitted because of the significant deforestation already made in previous years due to mass occurrence of bark beetle *I. typographus*. Since 2002, this area was influenced by its dynamic outbreak, with the culmination phase in 2007–2008 (Szabla 2013). The outbreak varied spatially (Grodzki 2009b); hence it was possible to select parts of the area in various phases.

Source, structure and analysis of data

For purposes of analyses performed in this work, we collected data on the size of the sanitary felling in forest sub-compartments of districts, Jeleśnia (2009–2010) and Ujsoły (2010–2011), assigned to the nine categories of damage (Table 1). All data were derived from the databases of the State Forests Information System (SILP).

Records concerning spruce were extracted from the obtained database and for further analysis only the ones relating to trees infested by cambiophagous insects were used, described in the system by the PZ symbol (code 23).

For the analysis of selected site and stand characteristics, which may affect tree mortality, forest inventory descriptions contained in the relevant SILP database tables of the forest districts studied were used. These were the features in particular:

– area of forest sub-compartment,
– forest site type,
– share of spruce (rounding to 10%),
– age of spruce (up to 80, 81–100 and over 100 years).

For the purposes of spatial analyses, copies of selected layers of digital maps were obtained from forest districts, containing:

– administrative division (forest compartments and sub-compartments),
– elevation isolines.

Forest survey descriptions and data on the tree mortality due to cambiophagous insects were com-

Table 1. Categories of timber processed within sanitary felling, registered in the State Forests IT System (SILP)

Category	Damage code		
	standing dead trees	broken trees	uprooted trees
Undetermined	PN (13)	ZN (11)	WN (12)
Infested by bark beetles	PZ (23)	ZZ (21)	WZ (22)
Left by bark beetles	PO (33)	ZO (31)	WO (23)

bined with a digital map layer of sub-compartments, obtaining a geometric database. It was supplemented with spatial attributes – altitude and slope exposition – derived from a digital terrain model generated from isolines. It was obtained by converting the compartment layer (polygons) into points by assigning the appropriate data to the centroids of polygons. Data on the dynamics of the mortality of trees infested by bark beetles were standardised by calculating the volume of trees per 1 ha for each polygon. In order to make the results more realistic, the area of referenced sub-compartments was reduced by multiplying it by the percentage of spruce. For the calculations, only sub-compartments where the felling of trees infested by bark beetles took place were used.

Source data collected in the form of a geometric database were visualised in order to illustrate the spatial diversity of the mortality of spruces infested by bark beetles in the area of research. For spatial data processing, ArcView 3.2 software with extensions was used.

Statistical analyses were also conducted to test the significance of the influence of selected factors (site and stand characteristics) on the dynamics of spruce mortality. Correlations, analysis of variance and post-hoc testing (Tukey HSD) were applied. Calculations were performed using MSExcel and STATISTICA v. 5.0 (StatSoft, Inc. 1997) software.

3. Results

Characteristics of the study area

Data on the intensity of spruce mortality due to bark beetle infestation in the years 2002–2011 indicate that the last outbreak, which culminated in 2007–2008, took a different course in each of the analysed forest districts (Fig. 1). However, in all of them during the study period, bark beetle populations were in retrogradation (Ujsoły and Węgierska Górka forest districts) or in a relative stabilisation (the Jeleśnia Forest District) phase.

The evidence of spatial diversity of the outbreak is seen in the results of visualisation of the spatial distribution of volume of trees infested by bark beetles in 2010–2011 (Fig. 2), especially between the southern part of the area, including Ujsoły and Węgierska Górka forest districts (retrogradation) and the eastern part of the Jeleśnia Forest District (stabilisation). For two of these units, detailed analyses were carried out, the results of which are given later in this article. In order to maintain uniform conditions within a massif, the scope of the analysis was narrowed to the whole Ujsoły Forest District (sub-districts: Ujsoły, Rycerka) and the Jeleśnia Sub-District in the Jeleśnia Forest District, lying in the Beskid Żywiecki (Fig. 2).

Stands surveyed in the Ujsoły Forest District occupy an area of almost 13.1 thousand ha, and within the Jeleśnia Forest District about 5.8 thousand ha. They grow on rich sites: the Jeleśnia District is dominated by the site group of the richest mountain forest (L – 51%) and rich mountain mixed forest (LM – 35%), while in the Ujsoły Forest District the rich mountain mixed forest prevails (LM – 72%), with a significant (25%) share of the richest mountain forest (L) (Fig. 3a). In both units, northern slope expositions dominate (from NE to NW), which are 53% and 47%, respectively, with a smaller percentage of southern expositions (Fig. 3b).

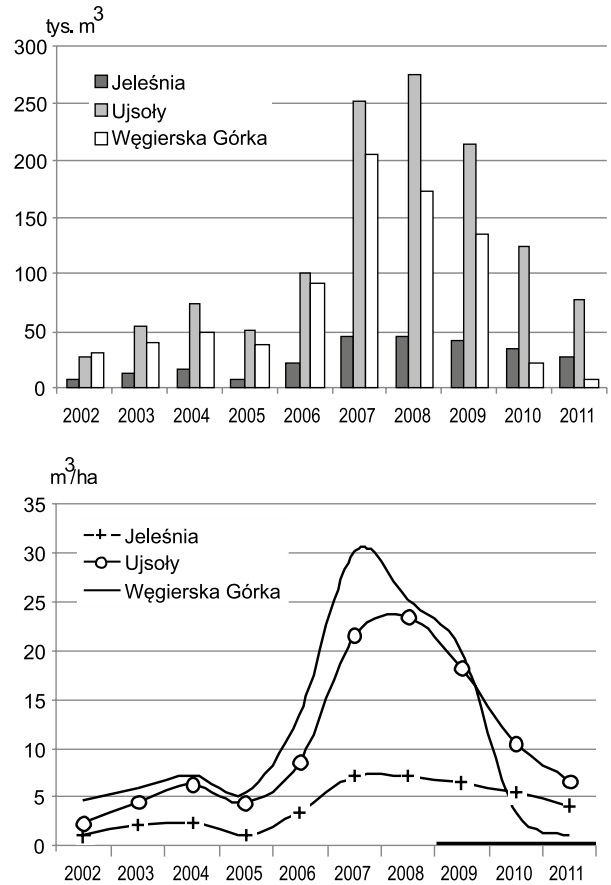
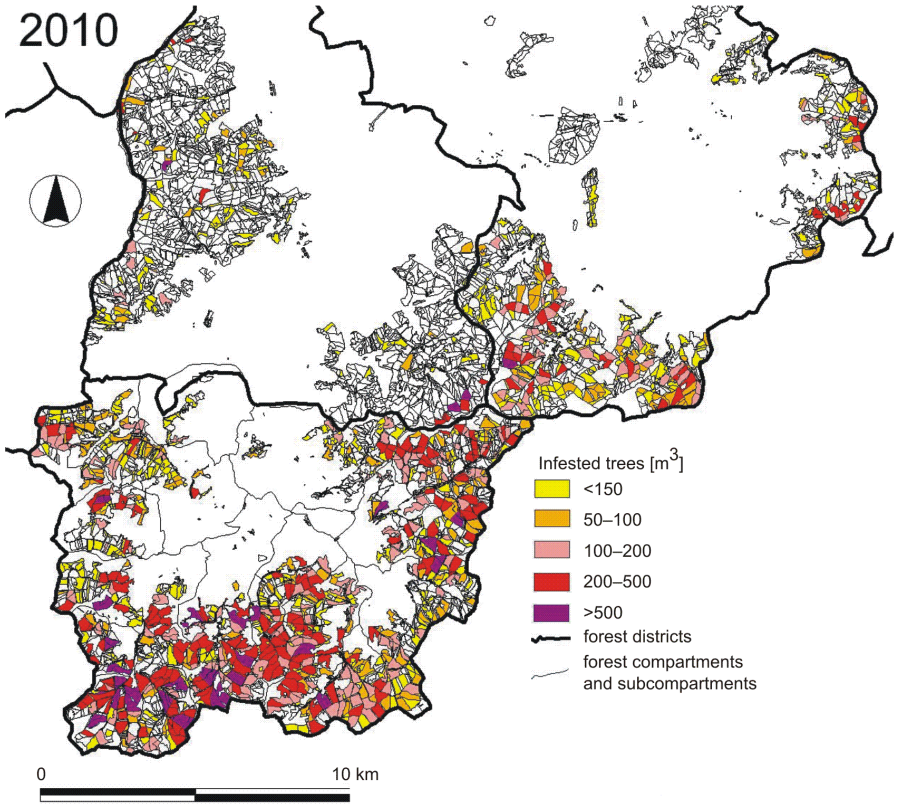


Figure 1. Volume of trees infested by bark beetles in the Forest Districts Jeleśnia, Ujsoły and Węgierska Górka in 2002–2011 – in total (above) and per 1 ha of stands (below). The period of research is marked by solid line.



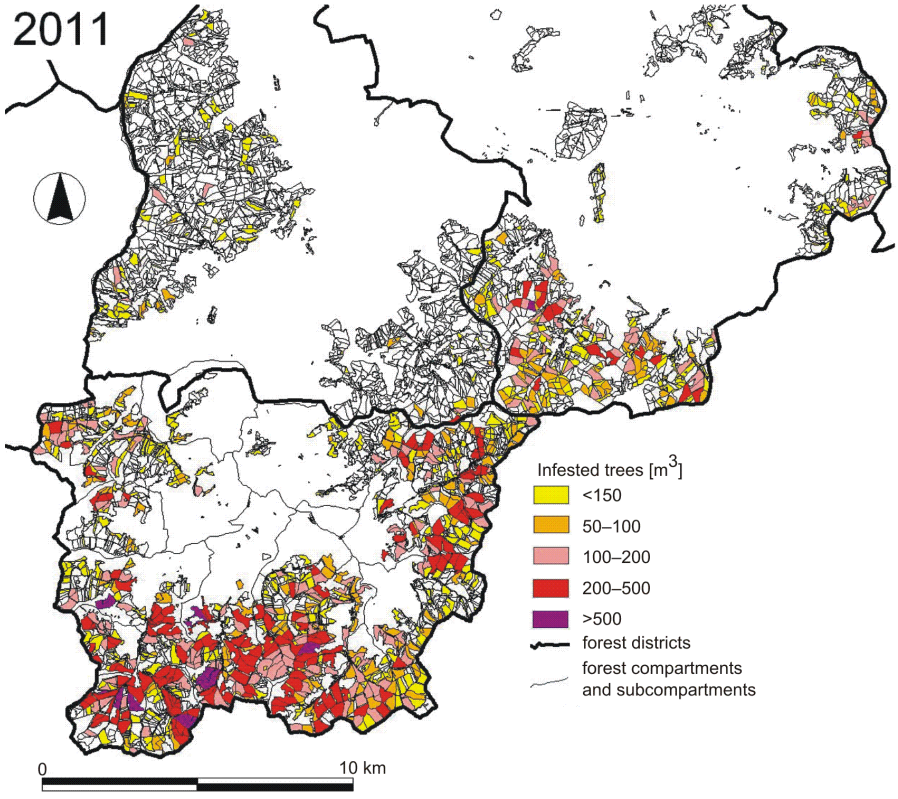


Figure 2. Intensity of spruce mortality due to bark beetle infestation in the study area in 2010 and 2011

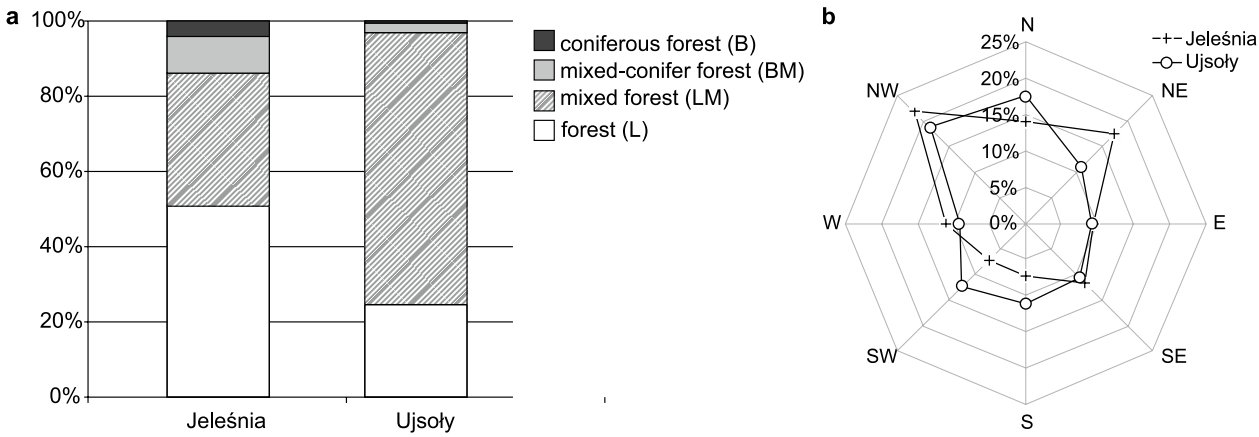


Figure 3. The percentage of poor (B) to rich (L) site types (a) and distribution of stands among slope expositions (b) in the Forest Sub-district Jeleśnia and in the Forest District Ujsoły

Factors influencing tree mortality

For the purposes of the work, databases from two analysed forest districts were compiled. The database of the Ujsoły Forest District contained 1712 records from both sub-districts, including 850 of 2009 and 862 of 2010, and the database from the Jeleśnia Forest Sub-District contained 644 records, including 334 in 2010 and 310 in 2011. The average actual intensity of spruce mortality due to bark beetle infestation (per 1 ha of forest sub-compartment) in the Ujsoły Forest District in 2009–2010 amounted to 14.51 m^3/ha, and in the Jeleśnia Forest District in 2010–2011 – 7.70 m^3/ha, while the values related to the area reduced by share of spruce were 15.68 and 12.21 m^3/ha, respectively. The actual and reduced values were strongly correlated in the Jeleśnia Forest District (r^2=0.51, $p<0.05$), but very poorly in the Ujsoły Forest District (r^2=0.12, $p<0.05$).

Altitude zone

In the Ujsoły Forest District, the volume of trees infested by bark beetles in 2009–2010 was the highest (20.41 m^3/ha) in stands growing at an elevation higher than 1000 m (Fig. 4a), and the influence of altitude was statistically significant (Table 2). In the Jeleśnia Forest District in 2010–2011, this volume was the highest (13.6 m^3/ha) in stands growing in the altitude zone of 800–1000 m above sea level (Fig. 4b), and these differences were also statistically significant (Table 2).

Slope exposition

In both analysed forest districts, the spruce mortality due to bark beetle infestation occurred at all expositions (Fig. 5), and its volume converted to the reduced area of 1 ha amounted to an average of 15.63 m^3 in the Ujsoły Forest District and 12.05 m^3 in the Jeleśnia Forest District. In the Ujsoły Forest District, the more intense mortality of infested trees was reported at south-east exposition (17.88 m^3/ha) and the western and south-western ones (17.29 and 16.08 m^3/ha, respectively). In the Jeleśnia Forest District, the highest tree mortality rates were found on the eastern slopes (14.24 m^3/ha) and the north-west and south-west ones (13.12 and 12.94 m^3/ha, respectively). Influence of the slope exposition in any of the analysed forest districts was not statistically significant (Table 2).

Share of spruce

The intensity of tree mortality in actual values was strongly correlated with the share of spruce in the stand (the Ujsoły Forest District: r^2=0.90, $p<0.001$; the Jeleśnia Forest District: r^2=0.86, $p<0.001$). Using data converted to the reduced area, the highest rates of spruce mortality were recorded in stands representing low share of spruce, with a weak upward trend observed in both forest districts with increase in its share in species composition, visible especially in classes 4–10 (Fig. 6). The effect of spruce share was statistically significant, and more noted in the Jeleśnia Forest District (Table 2).

Age of spruce

The intensity of spruce mortality due to bark beetle infestation takes the highest values in the stands aged 81–100 years, and slightly lower values (especially in the Ujsoły Forest District) in spruce forests over 100 years. In both units, the influence of age was statistically significant, the more strongly marked in the Ujsoły

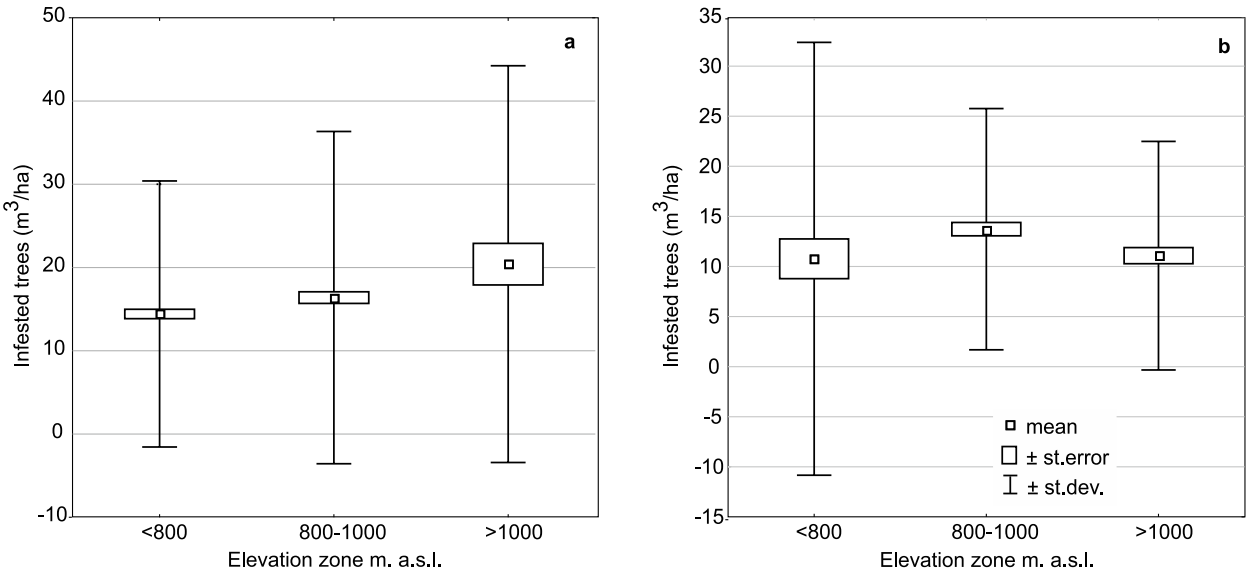


Figure 4. Volume of trees infested by bark beetles in elevation zones in Forest District Ujsoły in 2009–2010 (a) and in Forest District Jeleśnia in 2010–2011 (b)

Table 2. Effect of selected factors on the spruce mortality due to bark beetle infestation in the Forest District Ujsoły and Forest Sub-district Jeleśnia in 2009–2011 – results of one-way ANOVA

Factor	Ujsoły		Jeleśnia	
	F	p	F	p
Elevation zone (m a.s.l.)	5.456	**	3.625	*
Slope exposition	0.790	n.s.	1.311	n.s.
Percentage of spruce	2.192	*	4.062	***
Age of spruce	18.292	***	4.055	*
Forest site type	5.837	**	3.860	**

* p<0.05; ** p<0.01; *** p<0.001; n.s. – no significant differences

Forest District (Table 2), and the differences between the analysed age ranges were slightly different in the two forest districts (Fig. 7).

Site

In the Ujsoły Forest District, the tree mortality in 2009 occurred in four and in 2010 three forest types. In both years, it covered the forests growing on the richest sites: mountain forest (LG), mountain riparian forest (LLG), rich mountain mixed forest (LMG) and mountain mixed-conifer forest (BMG). While in the Jeleśnia Forest District, it covered seven types of forest site: richest mountain forest (LG) in two moisture variants, mountain riparian forest (LLG), rich mountain mixed forest (LMG) in two moisture variants, mountain mixed-conifer forest (BMG) and high-altitude coniferous forest (BWG). For the analysis, the distinguished site types were aggregated into four groups of fertility: richest forest (L), rich mixed forest (LM), mixed-conifer forest (BM) and coniferous forest (B). In the Ujsoły Forest District, the highest average rate of spruce mortality was found in the poor sites (BM), while the lowest in the most fertile (L) forest sites (Fig. 8a). In the Jeleśnia Forest District, in turn, this indicator received the highest value in the rich mixed forest, and slightly lower in mixed-conifer forest sites, while in the poorest high-altitude coniferous forest this rate was the lowest (Fig. 8b). It is worth noting that in the Ujsoły Forest District at an altitude of over 1000 m above sea level stands

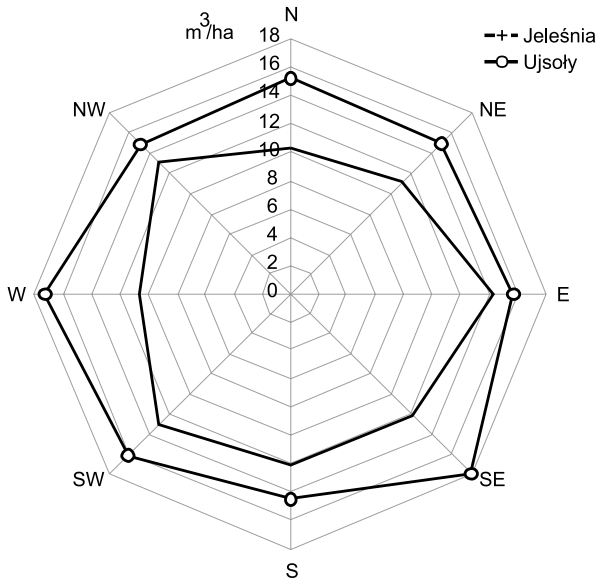


Figure 5. Volume of trees infested by bark beetles per 1 ha of stands in the Forest District Ujsoły (2009–2010) and Jeleśnia (2010–2011) by the slope exposition

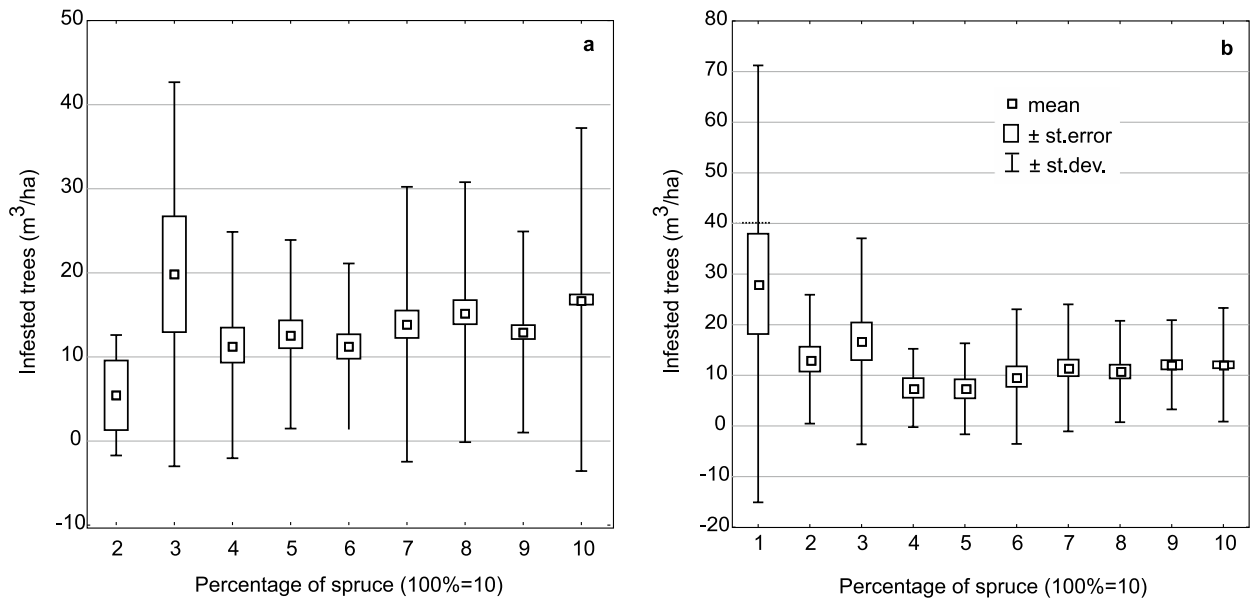


Figure 6. Volume of trees infested by bark beetles in the stands with various percentage of spruce in the Forest District Ujsoły in 2009–2010 (a) and Jeleśnia in 2010–2011 (b)

affected by spruce mortality were represented only by sites of mixed forest (LM) and mixed-conifer forest (BM), while in the Jeleśnia Forest District in the same altitude zone there were five site types – from the poorest to the richest ones. Generally, site fertility had a significant impact on the spruce mortality due to bark beetle infestation (Table 2), but the direction of this impact was not uniform in both units.

4. Summary and discussion

During the research carried out within the two forest districts and for the period of three growing seasons, data were collected and analysed describing the tree mortality due to bark beetle infestation and characteristics of forests affected by recent outbreak. From this analysis a complex set of factors emerges that shape

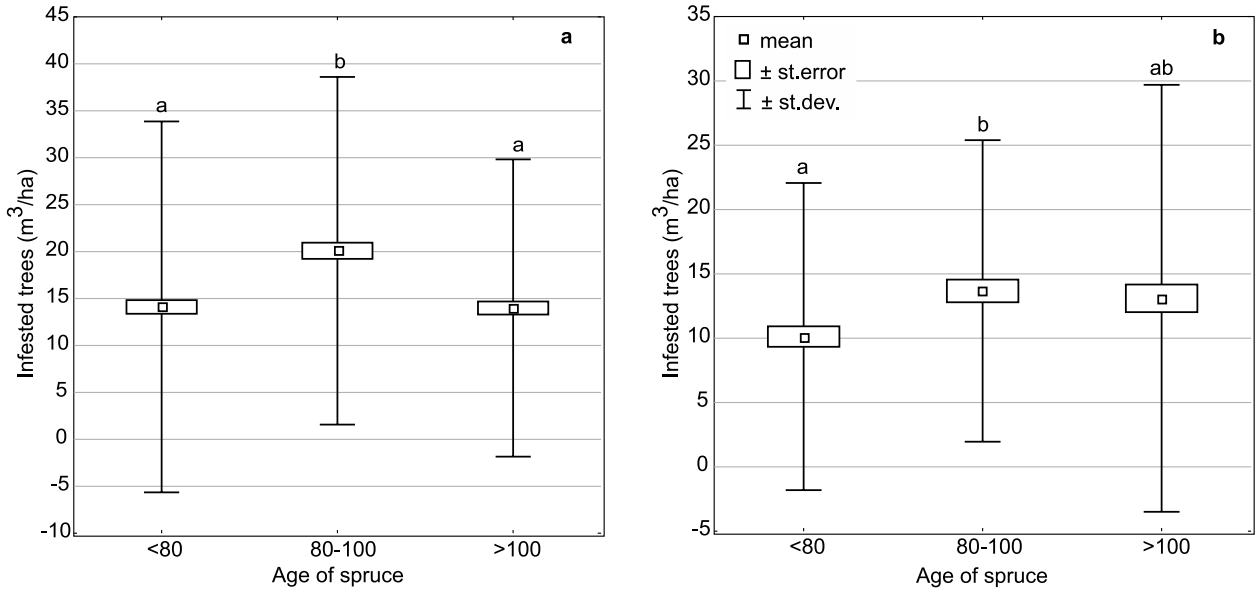


Figure 7. Volume of trees infested by bark beetles in the stands with various age of spruce in the Forest District Ujsoły in 2009–2010 (a) and Jeleśnia in 2010–2011 (b). Different letters indicate statistically significant differences.

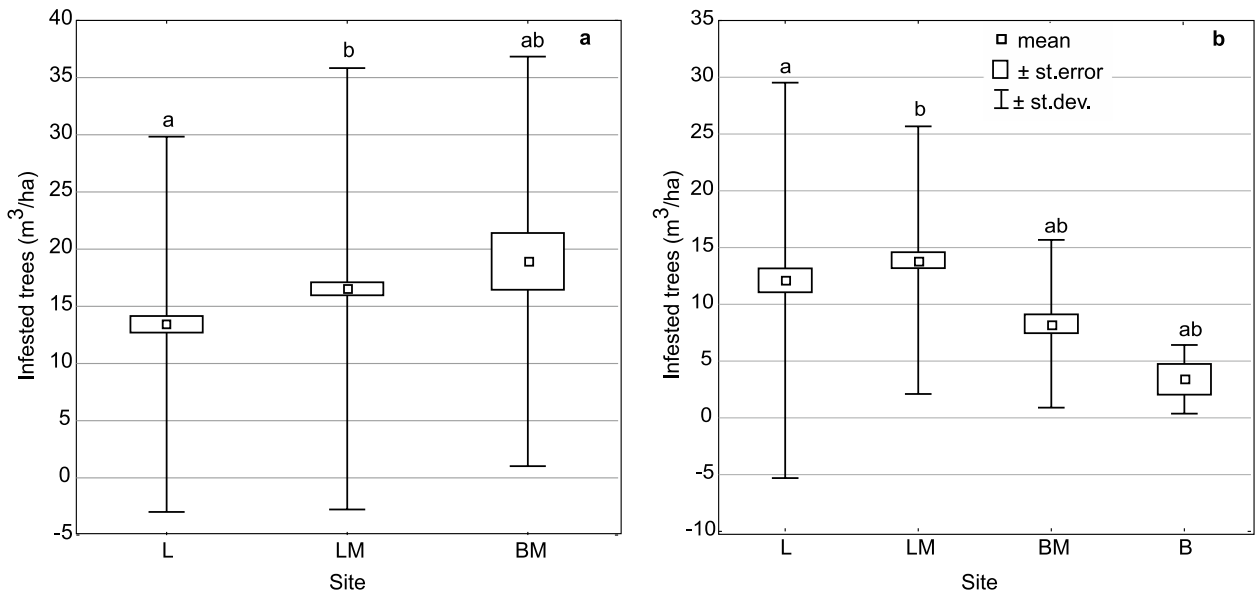


Figure 8. Volume of trees infested by bark beetles in the stands on various site types – from rich (L) to poor (B) in the Forest District Ujsoły in 2009–2010 (a) and Jeleśnia in 2010–2011 (b). Different letters indicate statistically significant differences.

the susceptibility of forest stands to *I. typographus* outbreak. It is known that the success of bark beetle attack on spruce depends on both the population of attacking beetles and susceptibility of trees and the consequent ability of the trees to defend themselves (Christiansen et al. 1987). The risk of bark beetle attack is affected by moisture conditions (availability of water in the soil), as well as slope exposition, the share of spruce and its growth trend (Lexer 1997). The observed dependencies, determined on the basis of data collected in the Beskid Żywiecki, are generally in compliance with the existing knowledge in this field, confirming

the role of these factors in shaping the susceptibility of forests to *I. typographus* attacks (Netherer, Nopp-Mayr 2005).

In mountain conditions, altitude is essential for the susceptibility of spruce to *I. typographus* attack. In the Węgierska Górka Forest District, situated in the Silesian and Żywiecki Beskids, where bark beetle outbreak has taken place a little earlier, the intensity of spruce mortality due to bark beetle infestation in its culmination phase (in 2008) took the highest values in altitude zones of 800–1000 m and more than 1000 m above sea level (Grodzki 2010). A similar pattern appeared a few years later in the neighbouring forest districts of the Beskid Żywiecki, where the intensity of spruce mortality due to bark beetle infestation was the highest in areas at more than 800 m above sea level. This was the result of vertical expansion of *Armillaria* disease in recent decades, affecting spruce susceptibility to bark beetle attack (Grodzki 2009b), as the area of the Beskid Żywiecki is now one of the most infested by this disease in Polish regions (Lech, Żółciak 2006). Despite the different causes and course of the last outbreak in the Beskidy Mountains and the one that happened in 1980s in the Western Sudetes, in both cases stands growing at higher altitudes have proven to be the most vulnerable to bark beetle attack (Grodzki 2009a).

In both analysed areas, spruce mortality occurred at all slope expositions, and the differences between them were small. The highest mortality rates were found at expositions from east through south to west, though the study area is clearly dominated by expositions close to north. It is generally consistent with current knowledge about the preferences of bark beetle (Grodzki et al. 2006), particularly with respect to insolation (Lobinger, Skatulla 1996; Turčani et al. 2000; Netherer, Nopp-Mayr 2005). Heavy mortality rates at all expositions, however, show that in terms of an outbreak the preference mechanisms in bark beetle are significantly weakened (Grodzki 2013).

An important feature determining the risk of bark beetle breeding is a high proportion of spruce, especially in the form of monoculture, as well as its high age (Lexer 1997; Netherer, Nopp Mayr 2005; Grodzki 2007b). In both forest districts, the spruce mortality expressed in actual values increased with share of spruce, which is a direct result of the amount of available breeding material. High reduced values of the volume of infested trees in stands with low (10%–30%) share of spruce, including the stands surrounded by pure or nearly pure spruce forest, may indicate the previously mentioned weakening of bark beetle preferences mechanisms during outbreak. Given the high proportion of spruce in stands of both units, amounting to 75% of the area in the Jeleśnia Forest Sub-District and 93% in the Ujsoły Forest District (Wyniki aktualizacji… 2010), it can be assumed that such situations occur commonly. Comparable (with a weak uptrend) amounts of infested trees in stands characterised by different share of spruce demonstrate a high level of bark beetle pressure on the stands where this tree species grows.

The risk of bark beetle outbreaks increases with the age of spruce. The resistance of trees in the first half of their life is determined by the considerable vitality, reflected in the increasing – to about 50–65 years old – growth (Capecki 1981). Most vulnerable to this attack are stands over the age of 100 years (Becker, Schröter 2000; Netherer, Nopp-Mayr 2005). In natural stands of the Tatra National Park, the intensity of spruce mortality due to bark beetle infestation increased linearly with spruce age, and the highest was in the spruce forests older than 180 years (Grodzki et al. 2006). In the Ujsoły Forest District, the highest rate of tree mortality is reported in stands aged 81–100 years and in case of the Jeleśnia Forest District in stands aged more than 100 years, in accordance with the rules known from the literature. It is also obvious that the older and the oldest stands provide larger volume, which also influenced the values of volume indices obtained.

Site conditions, especially nutrient content in the soil, are important for the susceptibility of spruce to bark beetle attack (Nef 1994; Dutilleul et al. 2000). Kula (1992) observed the increased spruce mortality on site types similar to the mixed forest. However, the results of the Beskidy Mountains are ambiguous. In the Ujsoły Forest District, with less diverse habitats, the spruce mortality was greater on the poorer sites (mixed-conifer forest – BM) that covered most of the area (72%), and the lowest on the richest sites (forest – L). However, in the Jeleśnia Forest District, more varied in terms of habitat, the tree mortality rates were the highest on mixed forest (LM) and mixed-conifer forest (BM) sites, representing a total of 45% of the sub-district, and the lowest on the least fertile – high-altitude coniferous forest (BWG) – whose share was 4%. It is possible that such a pattern resulted from distribution of forest site types. A noteworthy fact is that within the area of the Jeleśnia Forest Sub-District, with generally more fertile sites, the overall mortality of infested trees was lower than in the Ujsoły Forest District.

5. Conclusions

1. The greatest influence on the intensity of spruce mortality in analysed forest districts of the Beskid Żywiecki was share and age of spruce within stands, and smaller influence was altitude zone and site conditions. Slope exposition had no significant impact on the susceptibility of forest stands on the occurrence of bark beetles.

2. Ambiguous results of analyses of the bark beetle preferences in terms of the characteristics of stands studied indicate a weakening of its mechanisms for selecting trees for infestation during an outbreak and strong pressure on the stands.

3. Analysis of selected characteristics of trees and spruce stands in mountain conditions can be used to predict their susceptibility to bark beetle outbreak.

4. This method should be applied in the planning and implementation of active protection measures against bark beetle, both in managed forests and forests under active protection.

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