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ORIGINAL PAPER

Can sanitation cutting contribute to reduced mortality of Norway spruce *Picea abies* (L.) H. Karst., due to infestation by *Ips typographus* (L.)?

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ABSTRACT

The aim of the work was to determine whether actions to curb the abundance of spruce bark beetles can contribute to a reduction in mortality rates among spruce trees. The study was carried out in Poland's Białowieża Forest, by reference to two interpretation units, *i.e.* production forest stands (the 506 km^2 Managed Forest), and non-managed stands in the Strict Reserve of Białowieża National Park (the 46 km^2 Protected Forest). Empirical data were collected during the two outbreaks of spruce bark beetle of 2000-2004 and 2011-2015. During the first outbreak, classical protective treatments were applied to limit numbers of the insect in the Managed Forest, while no such treatments were applied in the Protected Forest. In turn, during the second outbreak, there were no protective treatments applied in the Protected Forest, while in the Managed Forest they were resorted to, to only a limited extent. In the Protected Forest, data on the volume of live spruce trees and of dead ones on which spruce bark beetles were breeding, were collected on 160 permanent sample plots. In the Managed Forest, volume data for live spruces were collected at 36,136 angle-count (Bitterlich) samples (2001), and on 10 720 circular sample plots (2011), while volume data for spruces killed by beetles were derived from continuous measurements carried out by members of the forest administration. Protective measures were assumed to be effective if: (1) during the first outbreak, the volume share of spruces killed by bark beetles (in relation to the initial volume of live spruces) was greater in the Protected Forest than in the Managed Forest, (2) during the second outbreak, the volume share of spruces killed by bark beetles was similar in both units. In the event, the share of spruces found to have been killed by bark beetles in the years 2000-2004 was five times as high in the Protected Forest as in the Managed Forest. In the years 2011-2015 the share of killed spruces was similar in both units. Control of the spruce bark beetle outbreak occurring in the Managed Forest in the years 2000-2004 had thus produced positive results. Treatments aimed at limiting the numbers and rates of reproduction of spruce bark beetles in production forests were found to have had an effect, or more specifically to have led to a reduction in the dynamics of the outbreak, and hence in the rate of spruce mortality.

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KEY WORDS

Białowieża, dead, forest, live, managed, protected, tree, protective treatment, volume

Introduction

The European spruce bark beetle *Ips typographus* (L.) is one of the best-known insect species (Skuhravý, 2002; Wermelinger, 2004; Grodzki, 2013). As an organism associated inseparably with Norway spruce *Picea abies* (L.) H. Karst., it establishes feeding and breeding sites in the phloem of live trees, in so doing leading inevitably to their dieback. As long as its populations remain low, the spruce bark beetle is a natural-selection factor, eliminating the weakest trees from the ecosystem. However, an increase in population sees the beetles begin to attack stronger trees as well. These seek to defend themselves, but may be overwhelmed where numbers of beetles feeding on them increase further (Christiansen *et al*., 1987; Kausrud *et al*., 2011). And in this respect, the spruce bark beetle has a considerable capacity to achieve rapid increases in population, thanks to the production of several (up to three main, and up to two sister) generations each year, along with resort to polygamy and efficient mechanisms of chemical communication that encourage aggregation. This ensures the possibility of more major outbreaks taking place, with consequences including increased or mass dieback of colonised spruce trees (Skuhravý, 2002; Grodzki, 2013).

Various protection methods are in fact used to try and limit dieback among trees that is being caused by bark beetles. The direct control methods relate to sanitation (the identification and removal or treatment of currently-infested trees), the use of semiochemicals: attractants used to attract and capture insects, and anti-attractants combined with attractants (the so-called ‘push--pull’ method) to drive the insects’ dispersion and limit tree infestation; and of course also spraying with insecticides. To save timber, value salvage (*i.e.* the removal of trees already killed and left by beetles) can be applied. The indirect control strategies encompass actions aiming to increase forest resistance and reduce vulnerability to bark beetles, such as: clearcutting, thinning, shorter rotation length and conversion of stands (Fettig *et al*., 2014). Of these, in the case of *I. typographus* outbreaks in Europe, the most typical measure involves the search for and removal of specimens whose bark is at the given time playing host to spruce bark beetles in their juvenile development stages. The purpose is thus to prevent a next generation of beetles from flying off (Grodzki, 2013; Fettig and Hilszczański, 2015). More generally, activities of this kind represent one aspect of an integrated approach to forest protection (Niemeyer, 1997; Grodzki, 2013).

However, the value of treatments seeking to reduce numbers of spruce bark beetles has been the subject of controversy, indeed all the more so in recent years, especially where forests enjoying various forms of protection are involved. In particular, an argument applied to oppose active methods of forest protection holds that the spruce bark beetle is actually a ‘key species’ in the development of ecosystems (Müller *et al*., 2008), or in the preservation of biodiversity (Kausrud *et al*., 2012; Beudert *et al*., 2015). Such discussions also tend to feature assertions regarding a lack of direct evidence on the effectiveness of measures to reduce populations of the spruce bark beetle (Markovic and Stojanovic, 2010; Fahse and Heurich, 2011), while efforts at treatment may have as much impact on natural predators as on the target insect itself (Weslien and Schroeder, 1999), while negative impacts on carbon sequestration may also be exerted (Seidl *et al*., 2008).

On the other hand, the literature indicates that a failure to take active protection measures – especially as an outbreak is gathering pace – favours rapid growth of the population of spruce bark beetles (Stadelmann *et al.*, 2013; Grodzki and Gąsienica-Fronek, 2018, Vanická *et al.*, 2020), just as the felling of colonised trees contributes to a reduction in the level of threat posed to forest stands (Jönsson *et al.*, 2012; Kausrud *et al.*, 2012). The control tactics are effective if they are applied congruently with appropriate stages in an outbreak's development (Raffa *et al.*, 2008). On the other hand, experience has shown that even a course of no action is not without consequence (Fettig *et al.*, 2007). Nevertheless, the importance of – and need for – active protection of stands in the interests of biodiversity protection is still under discussion.

The above opinions on reductions in numbers of spruce bark beetles make it clear that this is an important, if still-unresolved problem relating to both the economy and the protection of natural resources. In this situation, the authors undertook research aimed at using empirical data to determine whether actions seeking to limit numbers of spruce bark beetles in fact do, or do not, contribute to a reduction in rates of mortality in Norway spruce trees.

Material and methods

STUDY AREA. Białowieża (and Belovežskaâ) Forest, as a research object, is located in Poland and Belarus. Its area is 1345 km^2, of which the Polish part covers 592 km^2. In 1921, in the central part of Białowieża Forest (also within the current borders of Poland), a nature reserve known as 'Leśnictwo Rezerwat' was established over some 46 km^2, with this going on to serve as Białowieża National Park (BNP) from 1932 on (Fig. 1). The Park area was enlarged in 1996. The oldest part of BNP, enjoying strict protection status since 1929, is customarily called the BNP Strict Reserve.

Outside the National Park, there are three forest districts (FD) of Poland's State Forests organisation 'Lasy Państwowe' (*i.e.* the Białowieża, Browsk and Hajnówka FDs) that are engaged in managing the rest of the Polish part, which covers 506 km^2 (this also including areas not regarded as Białowieża Forest historically). The area managed by these forest districts includes nature reserves covering 122 km^2 in total (as of 2020).

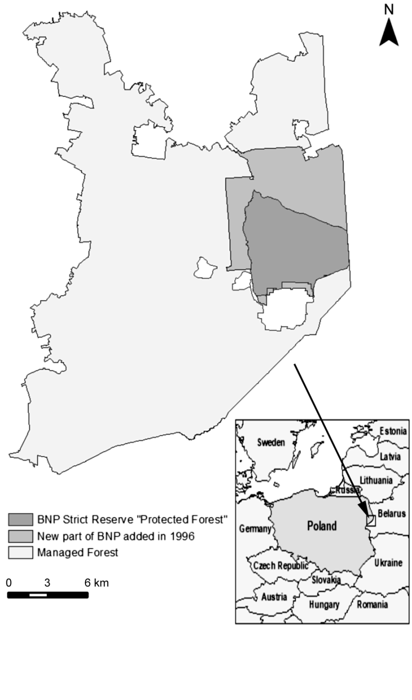

Fig. 1.
Białowieża Forest in NE Poland, with its two interpretation units in the form of the Protected Forest within the Strict Reserve of Białowieża National Park, and the Managed Forest located in production forest stands; forest in the new part of BNP was not included in this study

Białowieża Forest is located in the temperate transitional zone, with a prevalence (varying from year to year) of Continental over Atlantic influences (Faliński, 1986). Average annual values (for the 1948-2016 period) for the major climatic variables are: a mean air temperature of 6.6°C (-4.4°C in January, 17.6°C in July), precipitation of 639 mm, and a duration of snow cover equal to 83 days. In the 21st century, periods of drought during the months of tree growth have thus far occurred in 2000, 2001, 2003, 2006, and 2015 (Boczoń *et al.*, 2018). The terrain of Białowieża Forest is flat – the total altitudinal range is 68 m and the average altitude 167 m a.s.l.

Norway spruce was the main species constituting stands of Białowieża Forest. Its share by merchantable volume amounted to 26% in 2012. The European spruce bark beetle *I. typographus* has been the main species responsible for mortality in the Norway spruce, though certain other species like the double-spined bark beetle *I. duplicatus* (Sahlb.), engraver beetle *Pityogenes chalcographus* (L.) and (to a lesser extent) the small spruce bark beetle *I. amitinus* (Eichh.) have also contributed to dieback.

In the 21st century two spruce bark beetle outbreaks occurred in Białowieża Forest. During the first of these, in the years 2001-2004, classical protective treatments limiting the population of this insect were applied in the managed forest, while in the non-managed forest under strict protection (within BNP), no treatments of this kind were applied, given the aforementioned status (Michalski *et al.*, 2004). In stands of managed (production) forest, spruce trees colonised under bark by insects were identified for felling and transport out of the forest at an appropriate time (before beetles of a new generation emerged). Prior to 2008, it was also possible to resort to such measures in nature reserves enjoying 'active protection' status, provided that the relevant permit had been issued by the Regional Conservator of Nature. Effective outbreak limitation in forest stands managed by forest districts did prove possible at that time (Brzeziecki *et al.*, 2018). In the BNP area, a significant number of spruce trees died as a result of that outbreak (Miścicki, 2012).

In 2012, the newly-developed forest management plan for the three forest districts saw the Minister of the Environment review the annual allowable cut, and cap that from a proposed 107,400 m^3 to just 48,500 m^3. This denoted an intensity of cutting in managed stands as low as 1.3 m^3 ha^{-1} $year^{-1}$ (Scientific Council for Forestry, 2016). In forest stands in which at least 10% of trees were more than 100 years old, as well as those growing in wet or marshy habitats, all felling came to be prohibited.

2012 emerged as a year in which the second outbreak of the spruce bark beetle commenced. Protective treatments were again eschewed in the protected forest, while in the managed forest limitations arising from a natural resources protection policy were sustained (Blicharska and Van Herzele, 2015; Brzeziecki *et al.*, 2018). In the area under forest district management spruce trees colonised by bark beetles were still marked, but only a part of them were felled. The efficacy of protective treatments was limited significantly by the lack of any possibility of trees under attack in nature reserves and forest stands excluded from utilisation being felled. Additionally, in some forest districts, the volume of felled trees had attained the allowable ten-year-cut limit before 2017. The sequence of subsequent events (from 2012) did indeed lead to a mass outbreak of the spruce bark beetle. This leaves the outbreak as unprecedented in scale in the whole period since 1923 (Stereńczak et *al.*, 2020). Thus, between 2012 and 2016, the three forest districts operating in Białowieża Forest recorded the death of over 1 million m^3 of spruce trees (Fig. 2), as a result of their having been colonised by the beetles (Hilszczański and Starzyk, 2017; Brzeziecki *et al.*, 2018).

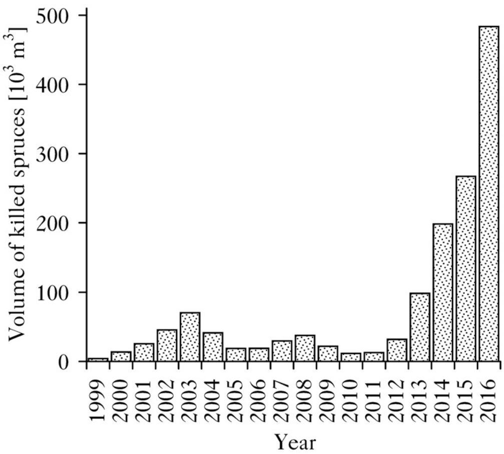

Fig. 2.
Intensity of damage caused to Norway spruces by the European spruce bark beetle, as presented in terms of the volume of trees killed by this insect in the managed part of Białowieża Forest (data from the Regional Directorate of the State Forests in Białystok)

RESEARCH CONCEPT. It was assumed that measures to limit spruce dieback in the wake of colonisation by spruce bark beetles were effective if:

– during the first outbreak (2001-2004), the share by volume of spruce trees killed (in relation to the volume of live spruces at the beginning of the outbreak) was higher in the protected forest than in the managed forest, where treatments were applied to limit the effects of the outbreak,
– during the second outbreak (2012-2015), when mitigation measures were not applied in the protected forest and applied to only a limited (far from the sufficient) extent in the managed forest, the proportions by volume of spruces killed by the beetles were similar in both parts of Białowieża Forest.

To verify the above assumption, two interpretation units were formed: the Protected Forest and Managed Forest (Table 1, Fig. 1). Both units were considered similar in terms of their proportions of forest habitats, average volumes of spruce, average densities of spruce trees with size (expressed by diameter) regarded as most attractive to the bark beetle. This meant a presumption that only differences in protective treatments limiting the population of bark beetles would cause differences in the mortality of Norway spruce.

MATERIAL. In the Protected Forest, August 2000 and August 2011 estimates were made of the merchantable volume of live spruce trees (of *dbh*=7.0 cm), to which the volume of dead trees of this species was related. To that end, data were collected from 160 uniformly-distributed permanent sample plots with 267×1067 m spacing. The plots were concentric, in the sense that trees of *dbh* 7.0-11.9 cm were measured in a 50 m^2 circle, while those of *dbh* in the range 12.0--35.9 cm were measured in a 200 m^2 circle, and those of *dbh* at least 36.0 cm over a 500 m^2 circle. The merchantable volume of individual spruce trees was determined by reference to diameter at breast height, height (estimated from the curve relating tree height to *dbh*) and a *dbh* shape figure after Bruchwald *et al.* (2000). Following two-year intervals (*i.e.* in the Augusts of 2002, 2004, 2013 and 2015), field measurements were repeated, with note being taken of trees that had died during the given period, as well as cause of death (not least, but not only, caused by the spruce bark beetle).

In the Managed Forest the merchantable volumes of live spruce trees were estimated in 2001 and 2011. Data from 36,136 angle-count (Bitterlich) samples with a basal area factor *k*=4 were used to inventory the forest in 2001. These measurements were made by employees of

Table 1.
Some features characterising the interpretation units in Białowieża Forest termed the Protected Forest and the Managed Forest

Feature	Units	Protected Forest	Managed Forest
Area	km^2	46	506
Proportion of forest habitats:	%		
marshy coniferous, mixed coniferous and mixed deciduous f.		10	1
mesic or wet coniferous and mixed coniferous forest		8	28
mesic or wet mixed deciduous forest		14	27
mesic or wet deciduous forest		54	32
swamp or riparian deciduous forest		14	12
Volume of Norway spruce (2000/2001)	$m^3\ ha^{-1}$	93	91
Density of Norway spruces (2011/2012)	ind ha^{-1}		
attractive to the bark beetle*) with *dbh*=20-72 cm		64	72
most attractive to the bark beetle*) with *dbh*=36-60 cm		15	18

*) according to Miścicki (2012)

the Forest Management and Geodesy Office in Białystok, to meet the needs of the forest management plan being prepared. The merchantable volume of spruces was calculated with a given angle-count sample on the basis of: the total cross-sectional (basal) area at breast height, the average height of trees and the *dbh* shape figure in tables from Trampler (1974). In 2011, the volume of live spruces was inventoried using data from 10720 circular sample plots, including those measured by employees of the Forest Management and Geodesy Office in Białystok, to meet the needs of the in-preparation forest management plan. Plot sizes ranged from 50 to 500 m^2, depending on the age class of the stand in which the sample plot was located. The merchantable volume of individual spruce trees was determined on the basis of diameter at breast height, height (estimated from the 'fixed curve' relating tree height to *dbh*) and a *dbh* shape figure (after Bruchwald *et al.*, 2000). To determine the volume of spruces killed by bark beetles, reference was made to data collected continuously by employees of forest districts located within Białowieża Forest. These data concerned spruce trees identified as having been colonised by the insects, with annotation in respect of felling and transport away from the area (only some dead spruce trees were removed post-2008). These data provided the basis for calculating the volume of spruce trees killed by bark beetles in the period from August 2000 to August 2004, and then from August 2011 to August 2015.

STATISTICAL ANALYSIS. In line with the research assumptions, verification sought to establish whether the average share of spruce trees that died (in relation to the volume of all spruces at the beginning of the studied periods):

– in the 2000-2004 period was higher in the Protected Forest than in the Managed Forest,
– in the 2011-2015 period was the same in the Protected Forest as in the Managed Forest.

The *Z*-test was used to evaluate differences between average values, as follows:

$$Z_t = \frac{\overline{q}_P - \overline{q}_M}{\hat{\sigma}_D} \qquad [1]$$

where:

$\overline{q}_P$, $\overline{q}_M$ – are the average shares by volume of spruces killed by bark beetles in the Protected and Managed Forests respectively, $\hat{\sigma}_D$ is the standard error of the sampling distribution difference between two proportions

$$\hat{\sigma}_D = \sqrt{(S_{qP}^2 + S_{qM}^2} \qquad [2]$$

S_q^2, S_{qM}^2 are the squared standard errors for the share by volume of spruces killed by bark beetles in the Protected and Managed Forests respectively

$$S_{qP}^2 = \frac{\overline{q}_P^2}{n_P(n_P - 1)} \cdot \left(\frac{\sum_{i=1}^{nP} x_i^2}{\overline{x}^2} + \frac{\sum_{i=1}^{nP} y_i^2}{\overline{y}^2} - \frac{2\sum_{i=1}^{nP} x_i y_i}{\overline{x} \cdot \overline{y}} \right) \qquad [3]$$

$$S_{qM}^2 = \frac{\overline{q}_M^2}{n_M(n_M - 1)} \cdot \left(\frac{\sum_{j=1}^{nM} x_j^2}{\overline{x}^2} \right) \qquad [4]$$

where:

n_P, n_M – are numbers of sample plots in the Protected and Managed Forests respectively,

x_i, x_j – are volumes of merchantable wood in live spruces in the *i*th sample plot in the Protected Forest and in the *j*th sample plot in the Managed Forest,

y_i – is the merchantable volume of spruces killed by bark beetles in the given period, in the *i*th sample plot within the Protected Forest.

The value of the *Z*-test statistic was compared with the critical value for the normal distribution. The *Z*-test was chosen because:

- in the case of the Managed Forest, no data on the volume of spruces killed by bark beetles in the two periods on a given sample plot were available;
- it was assumed that the merchantable volume of dead spruce trees in the two periods was determined precisely from the measurements of all trees identified as colonised by bark beetles;
- this being the case, the standard error of the share of dead spruces was affected only by the error of estimation inherent in the figure for the volume of live spruce trees.

To assess the differences in volume among live spruces in the Protected Forest between 2000 and 2011, a Student's *t*-test for paired samples was used. In turn, assessment of differences between 2001 and 2011 in the Managed Forest was achieved using a Student's *t*-test for independent samples. In all cases, a confidence interval (CI) for the mean was estimated at P=0.05. Statistical analyses were performed using the *Statistica 10* software (StatSoft, 2011).

Results

As of 2000, the average volumes of the live spruces in the two units proved to be similar. While in the Protected Forest the figure was 93 ±15 m^3 ha^{-1}, in the Managed Forest it was 91 ±1.0 m^3 ha^{-1}. Between August 2000 and August 2004, the average volume of spruces killed by bark beetles in the Protected Forest was of 17.6 ±9.4 m^3 ha^{-1} (*i.e.* 81,000 m^3 over the entire unit). This was a figure over five times as great as in the Managed Forest, where it was 3.4 m^3 ha^{-1} (*i.e.* 173,000 m^3 over the entire unit). A similar relationship was noted in the case of the share of spruce trees killed by bark beetles (Fig. 3). In the Protected Forest, this latter share was of 18.9 ±8.7%, which was significantly higher (at P<0.001) than in the Managed Forest, where it was 3.8 ±0.04%.

In 2011, the average merchantable volume of live spruces in the Protected Forest was lower than it had been eleven years previously (albeit only at borderline significance, P=0.055), at 80 ±14 m^3 ha^{-1}. This was therefore the opposite situation to that applying in the Managed Forest. In the latter unit, the average merchantable volume of live spruces in 2011 was greater than it had been in 2001 (P<0.001), at 114 ±1.8 m^3 ha^{-1}. The volume of spruces killed by bark beetles offered no basis for differentiating between the units in the years 2011-2015 (P=0.72). This time, slightly more spruces died in the Managed Forest (10.1 m^3 ha^{-1}, *i.e.* 512,000 m^3 over the entire unit) than in the Protected Forest (6.3 ±4.9 m^3 ha^{-1}, *i.e.* 28,800 m^3 in the entire unit). In the Managed Forest, the share of spruces killed by bark beetles in the period 2011-2015 was of 8.9 ±0.1%, this being at almost the same level as in the Protected Forest, where it amounted to 7.8 ±5.7% (Fig. 3).

Discussion and conclusions

Obtaining direct evidence of the effectiveness of protective treatments seeking to limit a population of bark beetles proves extremely difficult or even impossible. This is evidenced by the small number of published works addressing this issue directly. A study of the kind presented here requires the collection of material in two comparable forest units affected simultaneously by an outbreak, albeit simultaneously at a distance sufficient to preclude mutual influences resulting from the dispersion ability of *I. typographus* (Gries, 1985; Stadelmann *et al.*, 2014). This is not feasible in practice in the space that remains to us in Europe. However, many years ago, it was found that active control measures cannot stop an outbreak, but can affect the amplitude of reproduction, reducing the numbers of standing trees being eliminated, shortening the retrogradation period and limiting the magnitudes of material and natural losses (Capecki, 1978). This statement was for example confirmed during the outbreak of spruce bark beetles in the Tatra Mountains of the Polish-Slovak border over the last decade of the 20th century, where, in forest stands excluded from active protection, it lasted (in the retrogradation phase) about three years longer than in stands of spruce forest under active protection (Grodzki *et al.*, 2006).

On the other hand, in wind-damaged stands in Sweden, in which windthrown and broken trees as breeding material for *I. typographus* were not removed, the frequency of occurrence of spruce trees colonised by bark beetles was twice as great as where windthrown trees had been removed

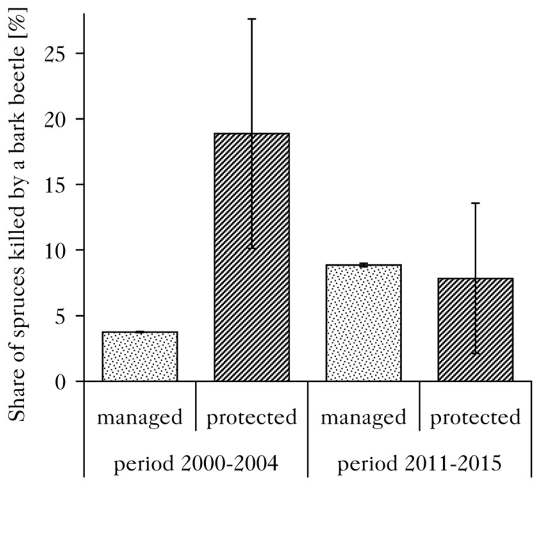

Fig. 3.

Share (by merchantable volume) of Norway spruces killed by bark beetles in stands of the Protected Forest (in the Strict Reserve of Białowieża National Park) and the Managed Forest within the wider Białowieża Forest, in the course of the outbreaks of 2000-2004 and 2011-2015 (mean ±CI at P=0.05)

(Schroeder and Lindelöw, 2002). Also Forster *et al.* (2003) demonstrated that active forest protection against bark beetles can contribute to up to a 50% reduction in the impact of infestation in comparison with forest stands in which activities of the above kind were not carried out.

Treatments applied do have positive effects, as when reproduction by spruce bark beetles in spruce stands in the Beskid Śląski and Beskid Żywiecki ranges in Poland was contained, with very intensive integrated protective treatments contributing to the arresting of a broad-scale, dynamic outbreak taking place in the first decade of the 21st century (Grodzki, 2012; Szabla, 2013).

The data presented in this paper come from Białowieża Forest, a site of large size by Central European standards (with a 592 km^2 area on the Polish side alone). This area falls under differentiated management systems (from managed forests through to those enjoying passive protection), and largely meets the criteria required if research on the effectiveness of treatments in containing outbreaks of the bark-beetle is to be undertaken. This does not apply to the assessment of the impact of the vicinity of forest stands under different protection regimes (Grodzki, 2016, 2021; Vanická *et al.*, 2020).

The results obtained make clear the success achieved in limiting outbreaks of spruce bark beetle in forest stands under management in the 2000-2004 period. The share of dead spruces was much lower than in the forest stands of the BNP Strict Reserve, in which no treatments were pursued and an outbreak could therefore develop unobstructed. On the other hand, a significant reduction of protective treatments (in essence in fact their absence) in the years 2011--2015 was associated with almost the same share of dead spruces in managed forest stands as in the BNP Strict Reserve at the same time. This corresponded with results obtained by Stereńczak *et al.* (2020). The remotely-sensed average density of dead spruce trees in July 2015 was slightly higher in Białowieża National Park (4.7 ind. ha^{-1}) than in the managed forest districts of Białowieża Forest (4.5 ind. ha^{-1}). A situation similar to that in Białowieża Forest was observed in spruce forest stands damaged by severe gales blowing in the Kościeliska Valley of Poland's Tatra Mountains, where removal of windthrown and broken trees just after the damage gave way to an abandonment of protective treatments and fast bark beetle reproduction in subsequent years (Grodzki and Gąsienica-Fronek, 2018).

The lesser volume of spruce trees dying in the Strict Reserve of BNP in the 2011-2015 period than in the 2000-2004 period may also represent a 'depletion' of feeding resources, as was the case in stands of the Bavarian Forest excluded from protective treatments in the 1990s (Heurich, 2009). Following the 2000-2004 outbreak, remaining (surviving) spruce trees in Białowieża Forest were largely confined to wet, marshy and very fertile mesic habitats, and were quite often present solely as an admixture or co-dominant tree species (Miścicki, 2016). On the basis of research by Seidl *et al.* (2007), it can be assumed that spruce trees in the latter situation have become less susceptible to the negative effects of infestation by spruce bark beetles. It might have been expected that in the Protected Forest due to a bigger share of the wet, marshy and very fertile mesic habitats spruce mortality dynamics would be lower than in the Managed Forest. Studies for the period 2015-2019 confirmed such expectations (Kamińska *et al.* 2021).

The effectiveness of removing colonised trees is conditioned by strict adherence to a time schedule, whereby spruces need to be taken out of the forest before a new generation of insects emerges (Wermelinger *et al.*, 2012). Reduced effectiveness of treatments is also a consequence of spruce bark beetles migrating in from neighbouring forest stands not subject to treatment (Mezei *et al.*, 2017). The removal of dead trees already abandoned by bark beetles is pointless in terms of forest protection, whereas the retention in the forest of such deadwood is quite justified in the interests of biodiversity protection (Kausrud *et al.*, 2012). Trzcinski and Reid (2008) believed that the effectiveness of protective methods could be limited by omitting certain colonised trees during sanitation cuttings. However, the results of American studies in this context (*e.g.* Hughes and Drever, 2001; Temperli *et al.*, 2014) should be treated with great reserve, as they concern other species of bark beetle and their host trees, as well as a spatial scale many times greater than in the forests of Europe, and even more so where the comparison is with Białowieża Forest (Hilszczański and Starzyk, 2017).

This paper presents the outcomes of research in which systematic measurements were made across the large Białowieża Forest study site. Unlike work based on simulation and modelling (*e.g.* Fahse and Heurich, 2011; Stadelmann *et al.*, 2013), this paper includes findings derived from extensive empirical material. It can be concluded that treatments seeking to limit numbers and rates of reproduction of spruce bark beetles in managed forests, using known and proven methods, have their effect. Specifically, they result in a reduction in outbreak intensity, as well as the rate of tree mortality. Bearing in mind the importance of treatments for biodiversity protection, a differentiated approach to methods applied should be recommended for Białowieża Forest (Grodzki, 2016; Witkowski, 2017), including treatments that limit numbers of spruce bark beetles, which, if carried out properly, can prove effective in forest stands affected by outbreaks.

To provide a complete view of situation, it would also be necessary to consider possible problems with management of the above kinds, its collateral effects, unclear cost-benefit aspects and potentially decreasing efficiency under a climate-change scenario that sees beetles behaving more aggressively even as trees are more and more under stress. However, we were not going to explore these aspects, as it was not the aim of our study, which was focused only on a question as to whether sanitation cutting can contribute to reduced mortality of Norway spruce *Picea abies*, due to infestation by *Ips typographus*. It seems that the data gathered are sufficient to justify our initial hypothesis concerning the positive effect of such active protection measures on the study area's spruce mortality induced by bark beetles.

Ultimately, results of the work are in contradiction to the opinion expressed in the report of the World Heritage Centre/IUCN (2018) as regards Białowieża Forest, that: '(…) it is not possible to demonstrate that the sanitary cuttings on the three forest districts can have a significant impact on controlling the outbreaks waves.'

Authorship contribution statement

S.M. – conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, supervision, visualization, writing – original draft (material and methods, results; discussion and conclusions – some parts), writing – review and editing; W.G. – writing – original draft (Introduction, Discussion and Conclusions), writing – review and editing

Conflict of interest statement

None declared.

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STRESZCZENIE

Czy cięcia sanitarne przyczyniają się do zmniejszenia śmiertelności świerka *Picea abies* (L.) H. Karst. w następstwie żerowania *Ips typographus* (L.)?

Celem pracy było określenie, czy zabiegi ograniczania liczebności kornika drukarza przyczyniają się do zmniejszenia śmiertelności świerków. Badania przeprowadzono na terenie Puszczy Białowieskiej, wykorzystując dwie jednostki interpretacyjne: las gospodarczy (Managed Forest, o powierzchni 506 km^2) i rezerwatowy (niezagospodarowany) w Rezerwacie Ścisłym Białowieskiego Parku Narodowego (Protected Forest, 46 km^2) (ryc. 1). Obie jednostki uznano za podobne ze względu na udział poszczególnych siedlisk leśnych, średnią zasobność świerka i przeciętne zagęszczenie świerków o wymiarach (wyrażonych pierśnicą) najbardziej atrakcyjnych dla kornika drukarza (tab. 1). Dane empiryczne zebrano podczas dwóch gradacji kornika drukarza w latach 2000-2004 i 2011-2015. Podczas pierwszej gradacji stosowano klasyczne zabiegi ochronne mające na celu ograniczenie liczebności tego owada w lesie gospodarczym (Managed Forest), lecz żadnych takich zabiegów nie zastosowano w lesie rezerwatowym (Protected Forest). Inaczej było podczas drugiej gradacji, gdy – tak jak poprzednio – nie wykonywano zabiegów ograniczania liczebności kornika drukarza w lesie rezerwatowym (Protected Forest), ale w lesie gospodarczym (Managed Forest) prowadzono je w małym zakresie, a w wielu miejscach nie wykonywano ich wcale. W lesie rezerwatowym (Protected Forest) dane dotyczące miąższości żywych świerków i tych zamarłych w następstwie zasiedlenia przez kornika drukarza *I. typographus* zebrano na 160 stałych powierzchniach próbnych. W lesie gospodarczym (Managed Forest) dane dotyczące miąższości żywych świerków zebrano na 36 136 próbach relaskopowych (w roku 2001) i 10 720 kołowych powierzchniach próbnych (w roku 2011), zaś dane o miąższości świerków zabitych przez kornika drukarza uzyskano na podstawie ciągłych pomiarów wykonywanych przez pracowników administracji leśnej (ryc. 2). Przyjęto, że działania ochronne były skuteczne, jeżeli: (1) podczas pierwszej gradacji udział miąższości świerków zabitych przez kornika (w odniesieniu do miąższości żywych świerków na początku gradacji) w lesie rezerwatowym (Protected Forest) był większy niż w lesie gospodarczym (Managed Forest), (2) podczas drugiej gradacji udział miąższości świerków zabitych przez kornika był podobny w obu jednostkach interpretacyjnych (częściach) Puszczy Białowieskiej. Rzeczywiście, podczas pierwszej gradacji w okresie 2000-2004 udział świerków zabitych przez kornika w lesie rezerwatowym (Protected Forest) był pięciokrotnie większy niż w lesie gospodarczym (Managed Forest), zaś podczas drugiej gradacji w okresie 2011-2015 udział takich świerków był podobny w obu jednostkach interpretacyjnych (ryc. 3). Oznacza to, że ograniczanie gradacji kornika drukarza w lesie gospodarczym (Managed Forest) w okresie 2000-2004 przynosiło pozytywne rezultaty. Stwierdzono więc, że wykonywanie zabiegów zmierzających do ograniczania liczebności i tempa rozrodu kornika drukarza w lesie gospodarczym przynosiło efekty w postaci zmniejszenia dynamiki gradacji tego owada, a w konsekwencji zmniejszenie śmiertelności świerków.