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RESEARCH

Infestation symptoms as indicators of a sustained bark beetle outbreak in conserved and managed Norway spruce forests in south-eastern Finland

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Abstract
European spruce bark beetle (*Ips typographus* L., SBB) infestations are extending in northern Europe due to increases in temperature and drought, which increase the risk of outbreaks in Norway spruce (*Picea abies* L.) forests. The severity of SBB damage may be decreased by timely detection and management measures. In this study, we analysed the SBB infestation levels of trees, the overall SBB damage at the stand level, the relationship between SBB damage and stand characteristics, and the effect of an outbreak over time on the volume and basal area in managed and conserved areas. We visually observed SBB symptoms at the stem level (entrance-exit holes, resinous flows, bark damage) and crown level (defoliation, discoloration) in 60 sampling plots in south-eastern Finland. These plots were established in an SBB outbreak area triggered by a severe wind disturbance in August 2010. Data were collected in 2014–2017 in conserved areas and in 2019–2021 in both conserved and managed areas. The results showed that in conserved areas, 70% of the trees were already highly infested in 2015, reaching 90% in 2017. During 2019–2021, the conserved areas were significantly more damaged than the managed ones. The volume of the stands decreased over time on average by 80% in conserved areas and 40% in managed areas, with the highest decrease occurring six to seven years after the initial SBB colonization. The damage estimated based on resinous flows and entrance-exit holes was similar regardless of the year or treatment. Our detection method may be used to support timely risk assessment and management of SBB outbreaks and decrease damage at the landscape level.

Keywords Forest disturbance · Forest management · *Ips typographus* · Tree symptoms · Ground-based visual observations

Introduction

Climate change induces multiple abiotic and biotic risks to forests and forestry in northern Europe (Venäläinen et al. 2020). Simultaneously, the risk of detrimental cascading events of combined abiotic and biotic disturbances increases. This is the case for severe bark beetle outbreaks, which can be triggered by large-scale wind damage or prolonged drought events (Marini et al. 2017; Venäläinen et al. 2020). The European spruce bark beetle (*Ips typographus* L., SBB; Coleoptera: Curculionidae, Scolytinae) (e.g., Seidl et al. 2014; Hlásny et al. 2021) is the most damaging biotic agent in Europe. It has caused extensive damage in Norway spruce forests in recent decades, especially in central

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and eastern Europe (Hlásny et al. 2019, 2021; Patacca et al. 2022).

The increasing trend in annual thermal sums due to climate warming (IPCC 2021; Ruosteenoja and Jylhä 2021) is escalating the risk of severe SBB outbreaks in the southern regions of the European boreal zone (Jönsson et al. 2012; Hof and Svahlin 2016; Venäläinen et al. 2020; Tikkanen and Lehtonen 2023). This is because climate warming is creating favourable conditions for SBB reproduction (Hlásny et al. 2019; Venäläinen et al. 2020). Moreover, increasing wind damage due to decreasing soil frost durations from late autumn to early spring (Peltola et al. 1999; Venäläinen et al. 2020), coupled with the presence of wind-damaged wood left on site, may augment the availability of breeding material for SBB, promoting a higher risk of SBB outbreaks (e.g., Hlásny et al. 2019).

SBB is a hazardous pest especially in older, mature Norway spruce (*Picea abies* (L.) H. Karst.)-dominated forests (Schlyter et al. 2006; Eriksson et al. 2007; Hlásny et al. 2019, 2021). Various factors have made Norway spruce forests susceptible to bark beetle outbreaks, such as the establishment of forests outside their natural range and on sites with lower soil water holding capacity; increases in growing stocks; and changes in forest age structure and composition (Hlásny et al. 2019; Jandl 2020). Initially, SBB attack Norway spruce trees or fresh wind-felled trees, but during an outbreak, SBB also attack nearby healthy standing trees (Eriksson et al. 2007; Kärvemo et al. 2016; Økland et al. 2016). Following SBB colonization of standing trees, the trees show infestation symptoms that are visible to the human eye at the stem (entrance-exit holes, resinous flow, bark damage) and crown (defoliation, discoloration) level (Blomqvist et al. 2018). These SBB attack symptoms appear in different stages of the attack (Kautz et al. 2023), with the entrance holes and resinous flows emerging in the earlier stage, while defoliation and discoloration occur in the later stage. Depending on the vitality of a tree, a very thin resinous flow may be exuded beneath the entrance holes due to the activated host defence mechanism (Baier et al. 2002). The bark of the spruce trees is gradually peeled away due to maternal galleries and feeding larvae in the phloem and inner bark later in the season (Grodzki and Fronek 2017; Schroeder and Cocoş 2018) and woodpeckers feeding on the larvae and pupae (Kautz et al. 2023). Crown symptoms, defoliation, and discoloration appear weeks later (Kautz et al. 2023; Huo et al. 2023) due to a loss of phloem tissue and penetrating hyphae of a blue-stain fungi blocking moisture transmission from roots to the crown (Netherer et al. 2021).

Considering that Norway spruce is one of the most economically valuable tree species in central and northern Europe (Caudullo et al. 2016), the SBB damage causes large economic losses for the European forestry sector (Hlásny et al. 2019). In Finland, Norway spruce accounts for 30% of the total volume of growing stock (Vaahtera et al. 2023). In managed forests, sanitation and salvage logging can be used to prevent the spread of SBB infestations (Schroeder and Lindelöw 2002). On the other hand, conserved forests are protected from any forest management activities (Korhonen et al. 2021; Vaahtera et al. 2023). Therefore, SBB infestations may also spread from conserved forests to neighbouring managed forests, causing large economic losses for forest owners (Hlásny et al. 2021).

Due to the increasing risk of SBB outbreaks and damaged areas in the past decades (e.g., Marini et al. 2017), there is an urgent need to expand our knowledge of time- and cost-efficient detection and monitoring methods. Recently in Finland, progress has been made in detection and monitoring using remote sensing technologies (e.g., Näsi et al. 2018; Junttila et al. 2022; Kanerva et al. 2022; Östersund et al. 2024). These technologies offer advantages for early detection by using multispectral or hyperspectral images (e.g., Junttila et al. 2022; Huo et al. 2023) and further detection and monitoring on larger scales (e.g., Fernandez-Carrillo et al. 2020). However, methods that require simple equipment and basic training, such as ground-based visual observations of individual trees attacked by SBB, could be an effective tool for forest owners, managers, non-professionals, and the scientific community. Promoting the use of ground-based visual observation to detect and monitor SBB-damaged areas based on evaluating SBB infestations at the stem and crown level could lead to more timely action and reduce the harmful effects on forests (Kautz et al. 2023).

In this study, we assessed SBB damage using ground-based visual observation of individual trees for SBB infestations at the stem (i.e., resinous flow, entrance and exit holes, bark damage) and crown (i.e., defoliation, and discoloration) level in managed and conserved Norway spruce-dominated forests. Based on this, we analysed the impact of SBB damage on stands during an SBB outbreak in south-eastern Finland. We focused specifically on comparing the conserved and managed forests regarding (i) the overall SBB damage of the stand, (ii) the relationship between SBB damage and stand characteristics, and (iii) changes in volume and basal area of the stands during an SBB outbreak. Our results demonstrate that detection of SBB damage based on tree symptoms is beneficial to diminish the harmful effects of an SBB outbreak. Our study is particularly relevant for the development of SBB damage assessments under boreal conditions. Our method could be used to support the development and validation of remote sensing-based detection methods and the detection and monitoring of SBB infestations by forest owners, managers, non-professionals, and the scientific community.

Materials and methods

Study area

The study area covered four Norway spruce-dominated forests, Viitalampi (0.74 km^2), Paajasensalo (0.56 km^2), Ryhmälehdonmäki (2.35 km^2) and Murtomäki (1.25 km^2), in the Ruokolahti municipality (61.17030 N 28.49010 S) in south-eastern Finland (Fig. 1). All experimental forests were situated within 10 km from each other to ensure similar climatic conditions. The forest site types in the area were mostly mesic (MT, *Myrtillus* type) and herb-rich (OMT, *Oxalis-Myrtillus* type) according to Cajander's site type classification (Cajander 1926; Mikola 1982). A detailed description of the ground floor vegetation and soil types can be found in Kosunen et al. (2019, 2020). The mature spruce stands were mixed with a lower proportion of Scots pine (*Pinus sylvestris* L.), downy birch (*Betula pubescens* L.), silver birch (*B. pendula* Roth), and a minor share of other deciduous tree species. The terrain in all experimental forests was generally flat with a mean altitude of 120 m above sea level (a.s.l.), except for the Paajasensalo site, which was situated on steeper ridges and had an altitude range from 115 to 160 m (a.s.l.). The mean air temperature and precipitation sum of the summer months (May–August) for the period 2014–2021 were 14.0 °C and 252 mm, respectively (Finnish Meteorological Institute). More detailed annual climate data can be found in Table A1 in the supplementary information (SI).

A major summer thunderstorm hit the region in late July 2010, followed by another one in early August due to exceptionally warm weather (Viiri et al. 2019). Following the storms, the area was a mosaic of completely windthrown stands, narrow gaps caused by downbursts and scattered windthrown trees. The large amount of freshly felled mature Norway spruces caused an SBB population explosion from 2011 onwards.

The management measures applied in the managed area included the removal of wind-felled trees if the volume of damaged spruces exceeded 10 m^3 per hectare and sanitation cuttings of highly infested forest compartments. These were responsive measures as a part of the compulsory SBB management in Finland according to the Forest damage prevention act (Finlex 2013). However, due to the high amount of fallen trees, the sanitation operation was not carried out on time, which increased the attacks of SBB. As a result, the colonisation gradually shifted from windthrown trees to standing and living trees in 2013 (Lyytikäinen-Saarenmaa et al., unpublished data). Based on our observations in the study area, SBB produced a second annual generation in several years since 2011 due to warm summer months (Table A1, SI).

Shortly after the large-scale wind damage, the Viitalampi (VL) and Paajasensalo (PS) sites were conserved as

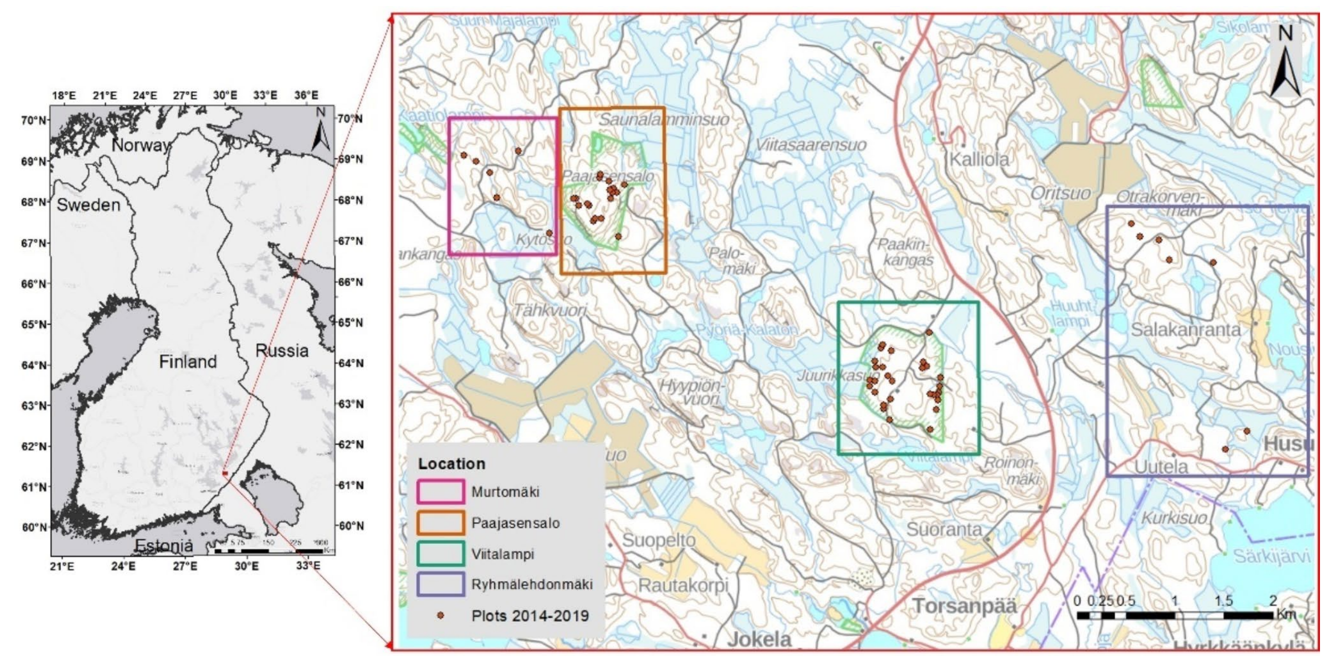

Fig. 1 Location of the Ruokolahti study area in southeastern Finland (left), and the sample plots in Murtomäki, Paajasensalo, Viitalampi and Ryhmälehdonmäki study sites (right). The sample plots were established during 2014–2019 (Table 1). The background map (right) contains data from the National Land Survey of Finland Topographic (background rasters covering M5411D and M5411F rectangulars, National Land Survey of Finland 2023). The map was created using ArcGIS Desktop 10.5 by Esri (Redlands, CA, USA) (ArcGIS is the intellectual property of Esri and is used herein under license. All rights reserved)

METSO (Forest Biodiversity Program for Southern Finland) sites, and no logging or transportation of dead wood were allowed there. The conservation decision made these over-mature stands highly susceptible to bark beetle reproduction (cf. Schroeder 2010; Kärvemo et al. 2014). The Murtomäki (MM) and Ryhmälehdonmäki (RM) sites were under normal forest management practice. These two areas were partially spared from the highest impact of the storms, and sanitation logging was conducted when required, particularly at susceptible forest edges. The SBB population became epidemic in RM after a mild drought and warm summer months in 2018.

Sampling plots and tree measurements

Sampling plots were established in the vicinity of windthrown areas in stands affected by SBB where living trees remained. The plots were established in the portions of stands experiencing visual signs of SBB damage. Each plot was expected to have a minimum of two dead or dying spruces surrounded by declining spruces with symptoms of SBB attack. In total, 60 circular plots were established between 2014 and 2019 (21 plots in 2014, 24 in 2015, 2 in 2016, and 13 in 2019), except in 2018 ('New' in Table 1). The plots were reassessed for SBB attack symptoms once a year in August in 2015–2017 and 2019–2021 ('ReM' in Table 1). Between 2014 and 2017, the stand characteristics and SBB attack symptoms for individual trees were assessed only in conserved areas, while between 2019 and 2021 they were assessed in both conserved and managed areas.

When each sampling plot was established, the location of the plot centre was recorded with a Trimble GPS device (Trimble Navigation Ltd., Sunnyvale, CA, USA) with an accuracy of up to 0.5 m after post-processing. In 2014–2017, circular plots with a radius of 5 m were established in conserved areas (VL and PS). In 2019, new damage spots were found in managed areas (MM and RM), where 13 circular plots with a radius of 10 m were established. The radius of field surveys for previous plots was also increased to 10 m due to a high proportion of dead and fallen trees within a radius of 5 m. Moreover, the trees that fell due to SBB-induced mortality, boosted by windy events in winters between 2017 and 2019, were excluded from the 2019 inventories.

The data collected from the sampling plots consisted of tree-wise measurements regarding tree characteristics and symptoms for SBB infestations. Tree-wise measurements consisted of diameter at breast height (dbh ≥ 10 cm, at 1.3 m above stem base), the height of the plot-wise median tree, the height of every seventh Norway spruce across the plots (Vuokila 1987), and the vitality status of each tree (e.g., dead, alive, fallen, broken, etc.). These characteristics were measured in the year when the plots were established and remeasured in 2019 when the size of the plot was increased. In addition, individual trees in the plots were located by measuring the distance and azimuth angle from the plot centre to the centre of each tree. The symptoms were evaluated annually using a scoring system based on the severity of the attack shown at the stem (entrance-exit holes, resinous flow, bark damage) and crown (defoliation, discoloration) level (cf. Blomqvist et al. 2018).

Table 1 Sampling plots in conserved (VL = viitalampi and PS = paajasensalo) and managed areas (RM = Ryhmälehdonmäki and MM = Murtomäki) in the Ruokolahti study area. New = newly established plots, ReM = remeasured plots

Study area	Variable	Plot size = 5 m radius							Plot size = 10 m radius		
		2014	**2015**		**2016**		2017	2019–2021*	**2019****		2020–2021
		New	**New**	ReM	**New**	ReM	ReM	ReM	**New**	ReM	ReM
PS	Plots	**13**	**5**	13	-	18	18	18	-	18	18
	Trees	**105**	**45**	105	-	150	150	106	**210**	150	360
	Trees/plot	**8**	**9**	8	-	8	6	6	-	-	20
VL	Plots	**8**	**19**	8	**2**	27	29	29	-	29	29
	Trees	**70**	**120**	70	**15**	182	197	139	**302**	139	441
	Trees/plot	**9**	**6**	9	**8**	7	7	5	-	-	15
MM	Plots	-	-	-	-	-	-	-	**6**	-	6
	Trees	-	-	-	-	-	-	-	**127**	-	127
	Trees/plot	-	-	-	-	-	-	-	**21**	-	21
RM	Plots	-	-	-	-	-	-	-	**7**	-	7
	Trees	-	-	-	-	-	-	-	**109**	-	109
	Trees/plot	-	-	-	-	-	-	-	**16**	-	16
Total	Plots	**21**	**24**	21	**2**	45	47	47	**13**	47	60
	Trees	**175**	**165**	175	**15**	332	347	245	**748**	289	1037

* In 2019, the fallen trees that were killed by SBB were excluded from the inventory

** In VL and PS, there were no newly established plots, but there were new trees included in plots with a 5- and 10-m radius

Infestation symptoms assessment and scoring

The symptoms for SBB infestation were assessed in the years when the plots were established and the following years until 2021, except 2018 (see Table 1). The assessment was done from mid to late August when all the stem and crown symptoms were visible and the impact of SBB on tree vitality was relevant. All living and dead standing spruces (dbh ≥ 10 cm) in the plots were assessed and ranked according to the severity of the symptoms. The entrance and exit holes were assessed up to a height of 2 m, resinous flow and bark damage were assessed up to the lowermost branch, while defoliation and discoloration were assessed from a distance corresponding to approximately a tree height as was done by Blomqvist et al. (2018). Each visual symptom provided a value from one to three (symptoms on tree stem) or one to four (symptoms on crown area) (Table 2). Examples of SBB tree symptoms can be seen in Fig. B1, SI.

The scoring classifies each tree into three categories of infestation: *not visually observable* (*NotVO*; score 1), *moderate infestation* (score 2 for stem symptoms and 2 or 3 for crown symptoms), and *high infestation* (score 3 for stem symptoms and 4 for crown symptoms).

The SBB damage (damage index of the plot, DIplot) was calculated using the scoring values of each symptom for all the spruces in the plot. Firstly, a damage index (DI) was calculated for each symptom of the tree by dividing the score recorded during field assessment by the maximum score it can take (Eq. 1). Secondly, the damage index of the tree was calculated using Eq. 2. Lastly, the SBB damage of the plot (DIplot) was calculated as the average DI of all the trees from the plot (Eq. 3). DIplot took values between 0 and 1, providing an estimate about the degree of damage (0: not damaged; 1: completely damaged).

$$DIs_{holes/resin/bark} = \frac{Field\ score}{3} \quad \text{or} \quad DIs_{defoliation/discoloration} = \frac{Field\ score}{4} \tag{1}$$

$$DI_{tree} = \frac{DI_{holes} + DI_{resin} + DI_{bark} + DI_{defoliation} + DI_{discoloration}}{5} \tag{2}$$

$$DI_{plot} = \frac{\sum DI_{tree}}{N}, \tag{3}$$

where N is the number of trees in the plot

Table 2 Ranking of infestation symptom scores and description of the visual symptoms indicating the severity of SBB attack

Symptom	Score	Description
Hole (entrance and exit)	1	0 holes
	2	≤ 10 holes
	3	> 10 holes
Resinous flow	1	0 spots
	2	1–30 spots
	3	> 30 spots
Bark damage	1	No damage
	2	Moderate damage
	3	High damage
Needle discoloration	1	Green
	2	Yellowish–yellow
	3	Reddish–red
	4	Grey (dead tree)
Defoliation	1	0–24%
	2	25–49%
	3	50–74%
	4	75–100%

Data analysis

The data analysis was carried out using R (version 4.2.2 and 4.2.3) and R Studio (version 2022.12.0-353, R Core Team 2017), mainly using the tidyverse package (v2.0.0: Wickham et al. 2019). The statistical analysis involved several steps. First, the Shapiro–Wilk test was used to test the normal distribution of the data (Wilcox 2009). Second, a parametric mixed-design ANOVA was used to investigate differences in the damage index of the plots among different treatments (conserved and managed) and years (2019–2021) (Dudek 2023). In this analysis, the year was used as the within-group variable, and the treatment as the between-group variable. Pairwise comparisons within each year and treatment were conducted using the Tukey method. Third, the unpaired *T*-test with Bonferroni correction was used to examine differences in the SBB damage of the plots, as indicated by each symptom separately (i.e., resinous flow, entrance and exit holes, bark damage, defoliation, and discoloration). This was assessed separately for each year and treatment. Fourth, the unpaired *T*-test was used to determine whether the change in DIplot from 2019 to 2021 differed between the treatments (Wilcox 2009). Fifth, the Pearson's correlation coefficient was used to assess the relationship between DIplot in 2019 and different stand variables (Wilcox 2009). In this analysis, highly correlated variables (r > 0.7) were excluded. Lastly, a Boosted Regression Tree model (BRT: Elith et al. 2008) estimated the extent to which the non-correlated variables explained the variability in DIplot, using the gbm package (version 2.1.8.1; Ridgeway and Ridgeway 2004). The model utilized a Gaussian distribution and fitted 5,000 decision trees to determine the best predictors.

Results

Observed SBB infestation levels of trees

The overall severity of SBB infestation differed according to the size of the plots in conserved areas (see figures for conserved areas in Fig. 2A and B). The trees in the 5-m-radius plots had high levels of infestation in 2014 regardless of the symptom type (> 50% of the trees). Between 2015 and 2021 the infestations increased so that over 80% of the trees were highly infested at the end of 2021 (Fig. 2A). For the trees in 10-m-radius plots (established in 2019), the overall infestation levels were lower (Fig. 2B) due to the larger size of the plots, showing the advance of the infestations from the infestation spot (the centre of the plot). In addition, the levels of infestation were higher in conserved areas compared to managed areas. In the conserved areas, around 50% of the trees were highly infested in 2019 and around 55% by 2021 (5% increase). In the managed areas, only around 4% of the trees were highly infested in 2019 and around 12% (8% increase) by 2021.

The proportion of trees showing high infestation levels based on resinous flow, attack holes, bark damage, and defoliation was greater than that based on discoloration. For example, in 2021 in the managed areas (Fig. 2B, Managed), 14% of the trees presented high infestation levels according to resinous flow, entrance-exit holes, bark damage, and defoliation, while only 4% did so based on needle discoloration. In the conserved areas, all the studied symptoms gave evidence for high levels of infestation for over 50% of the trees. However, based on discoloration, 43% of the trees had a green crown (score 1 in Table 2) in 2021.

SBB damage in the plots

Large numbers of highly infested trees in the conserved areas resulted in a high damage index at the plot level. This was observed especially for plots in the conserved areas where the trees were situated within a 5-m radius from the centre of the damage spot. The SBB damage (DIplot) was already 0.9 (max 1.0) in 2014, with an increase of 6% by 2021 (Fig. C1, SI).

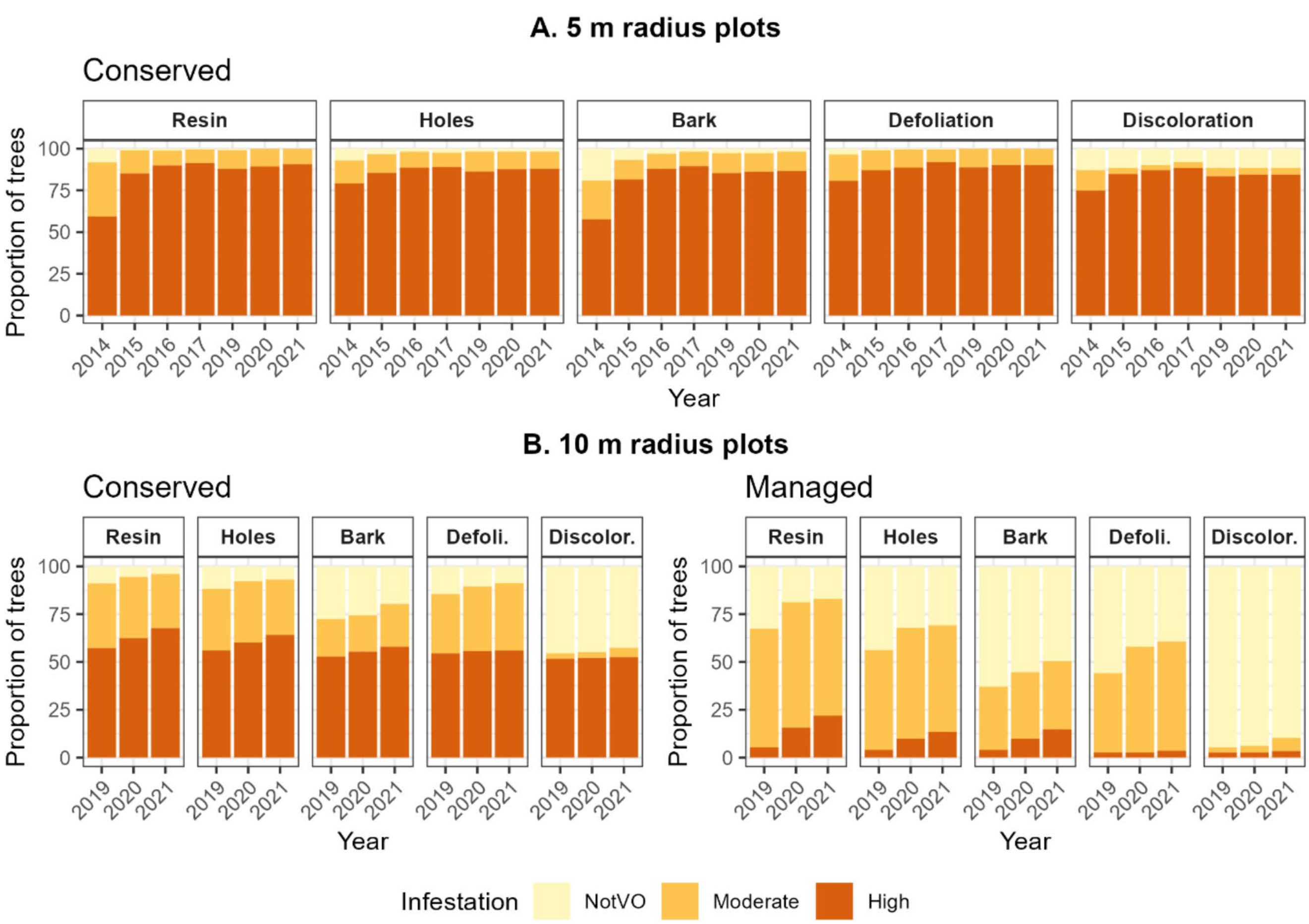

Fig. 2 The SBB infestation levels of the trees in plots with a 5-m (**A**) and 10-m (**B**) radius, in conserved and managed areas. The light colour represents a not visually observable (NotVO) infestation level and the dark colour represents high infestation levels

Considering the number of trees with not visually observable (NotVO) or moderate infestation levels in the 10-m-radius plots (Fig. 2, B), the SBB damage was generally lower. However, in this case, conserved areas had higher damage index values compared to managed areas (DIplot, Fig. 3A). The overall DIplot in the conserved areas was 0.75 in 2019, with an increase of 5% by 2021. While in managed areas the initial DIplot was 0.46, with an increase of 15% by 2021. Thus, the SBB damage in conserved areas was significantly higher than that in managed areas annually for the period 2019–2021 (P-value < 0.0001) (Table D2 abc, SI). However, in conserved areas, the change in DIplot between 2019 and 2021 was significantly lower than that in the managed areas (P-value < 0.05), showing the retrogradation phase in the conserved areas.

When the damage was analysed separately by each symptom (i.e., resinous flow, attack holes, bark damage, defoliation, and discoloration), in general, the symptoms had unequal contributions (DIs_plot, Fig. 3B). An exception was for the damage indices given by resin flows and entrance-exit holes, which were statistically similar regardless of the year or treatment (T-test; P-value > 0.05 at a confidence level of 95%; Table D1, SI). Additionally, the damage index given by defoliation in the conserved areas

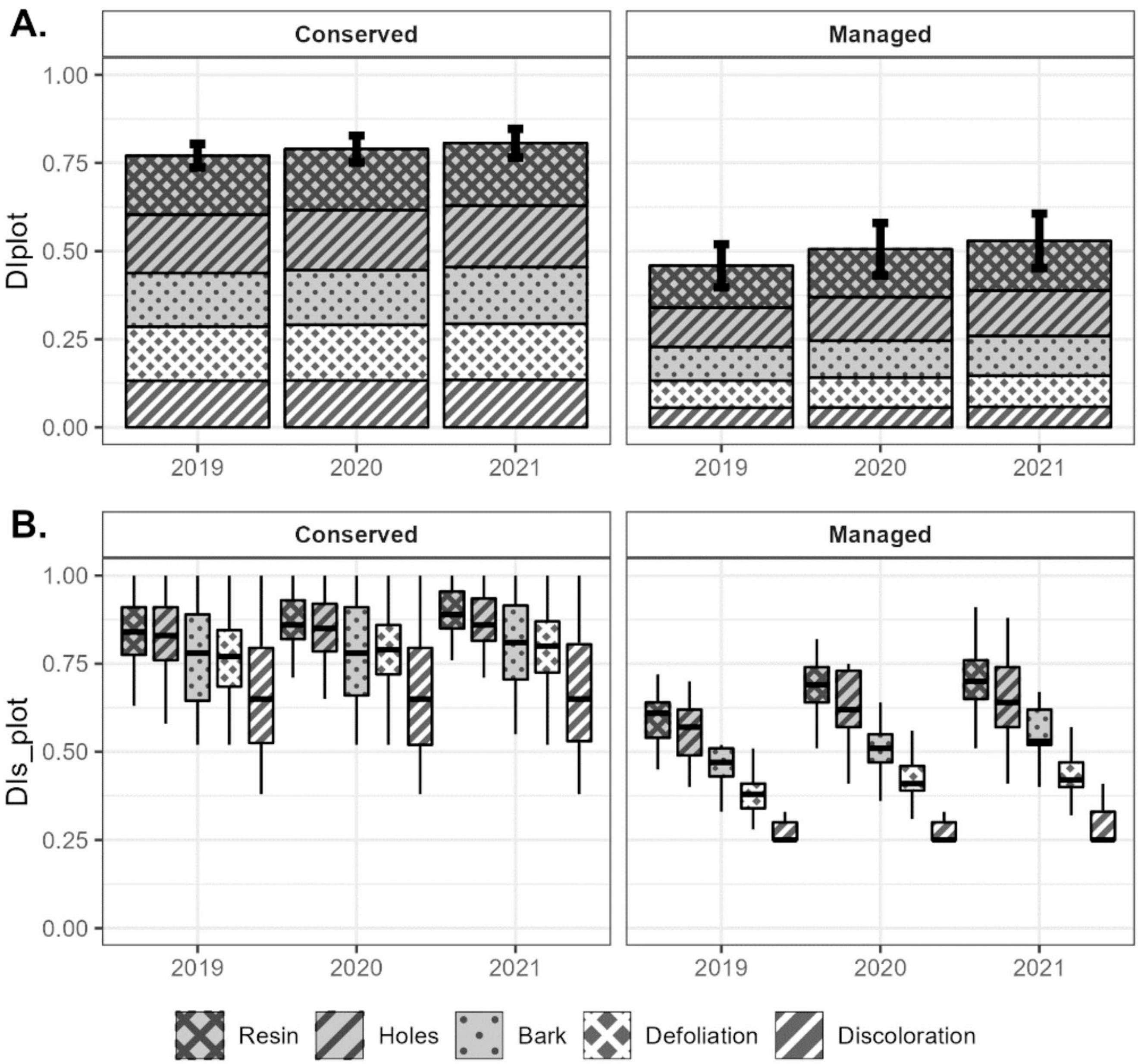

Fig. 3 **A** The average SBB damage (DIplot) of the 10-m-radius plots in conserved and managed areas. The different patterns in the bars represent the share of each symptom contributing to DIplot. The error bars represent standard error. **B** The boxplots show the SBB damage according to each symptom separately at the plot level (DIs_plot)

was statistically similar with the ones given by bark damage and entrance-exit holes. Resinous flows and entrance-exit holes showed on average a higher damage index (i.e., 0.83 in conserved areas and 0.57 in managed areas in 2019), while the lowest damage index was shown on average by discoloration (i.e., 0.65 in conserved areas and 0.28 in managed areas in 2019).

The relationship between SBB damage index and stand variables

The SBB damage index values significantly correlated with the stand basal area of the living trees and the age of spruce, which together explained over 50% of the variation of DIplot (Table 3). There were strong negative correlations between the basal area of the living trees and the volume of the living trees. On the contrary, there were strong positive correlations among the variables related to dead trees (Correlated variables, i.e., proportion, basal area, and volume of dead trees; Table 3).

There was a weak correlation between SBB damage and the proportion of spruce, explaining only 11% of the variation of damage index values. This may be because 85% of the plots had more than 80% spruce. In conserved areas, more than half of the plots with over 60% spruce were highly damaged in 2019 (Fig. C2, SI). The SBB damage showed a weak correlation with the proportion of both large and small spruces, likely due to the high infestation rate (> 50%) across all diameter classes in conserved areas (Fig. C3, SI).

Changes in characteristics and the dynamics of tree mortality during an SBB outbreak

For the plots with a 5-m radius in conserved areas, there were significant differences in the stand basal area, volume, and density between the two periods (2014–2017 and 2019–2021; Fig. 4A; subfigures a. b. c.). For the plots with a 10-m radius (Fig. 4B), the conserved areas generally had larger variations in stand characteristics than the managed areas. Of the stand characteristics measured, only the proportion and the average age of Norway spruce were significantly different (Fig. 4B; subfigures e., f.). Hence, conserved areas had a significantly lower proportion of Norway spruce and older trees on average. The median of the basal area weighted mean diameter (Dba) was similar in both conserved and managed areas, but a higher variation was observed in conserved areas (Fig. 4AB; subfigure d.).

The standing volume and basal area decreased as a result of increasing tree mortality and number of fallen trees due to SBB damage over time (Fig. 5). In plots with a 5-m radius in conserved areas, both volume and basal area decreased annually on average by 10%. In plots with a 10-m radius, the decrease was smaller: on average 6% per year in conserved areas and 3% per year in managed areas. However, the largest decrease (25%) was observed between 2017 and 2019. Consequently, the trees started falling 6–7 years after the initial colonisation. The dead trees remained standing for a while before falling, which explains a high proportion of dead trees in conserved areas, being over 80% throughout the study period (Fig. 5A). In the conserved areas with 10-m-radius plots, the trees killed by SBB represented 40% of the standing trees, while in the managed areas, the corresponding proportion was negligible (Fig. 5B).

Discussion

Evaluation of the methodology

In this study, we evaluated symptoms once a year in August, when both early symptoms (resin flows and entrance-exit holes) and late symptoms (bark damage, crown defoliation, and needle discoloration) were visible (Kautz et al. 2023,

Table 3 The correlation coefficients (r) showing the relation of DIplot with the stand variables and the variation in damage score explained by each variable (BRT). The analysis was done based on the information for 2019

Stand variable	*r*	BRT (%)	Correlated variables (*r* > 0.7)
Basal area of the living trees (m^2/ha)	**−0.79***	**38.76**	+ Volume of the living trees (m^3/ha)
			− Proportion of the dead trees (%)
			− Basal area of dead trees (m^2/ha)
			− Volume of the dead trees (m^3/ha)
Age of spruce (years)	**+0.49***	**14.95**	
Volume of spruce (m^3/ha)	−0.12	14.47	+ Volume of the stand (m^3/ha)
			+ Basal area (m^2/ha)
Proportion of basal area occupied by spruce (%)	−0.23	10.92	− Basal area of other species (m^2/ha)
			− Volume of other species (m^3/ha)
Proportion of spruce with big diameters (DBH > 30 cm)	+0.20	10.55	− Basal area weighted diameter (cm)
Proportion of spruce with small diameters (DBH < 20 cm)	−0.05	10.35	− The proportion of spruce with diameters 20–30 cm

* *P*-value < 0.05

+, positive relationship and −, negative relationship

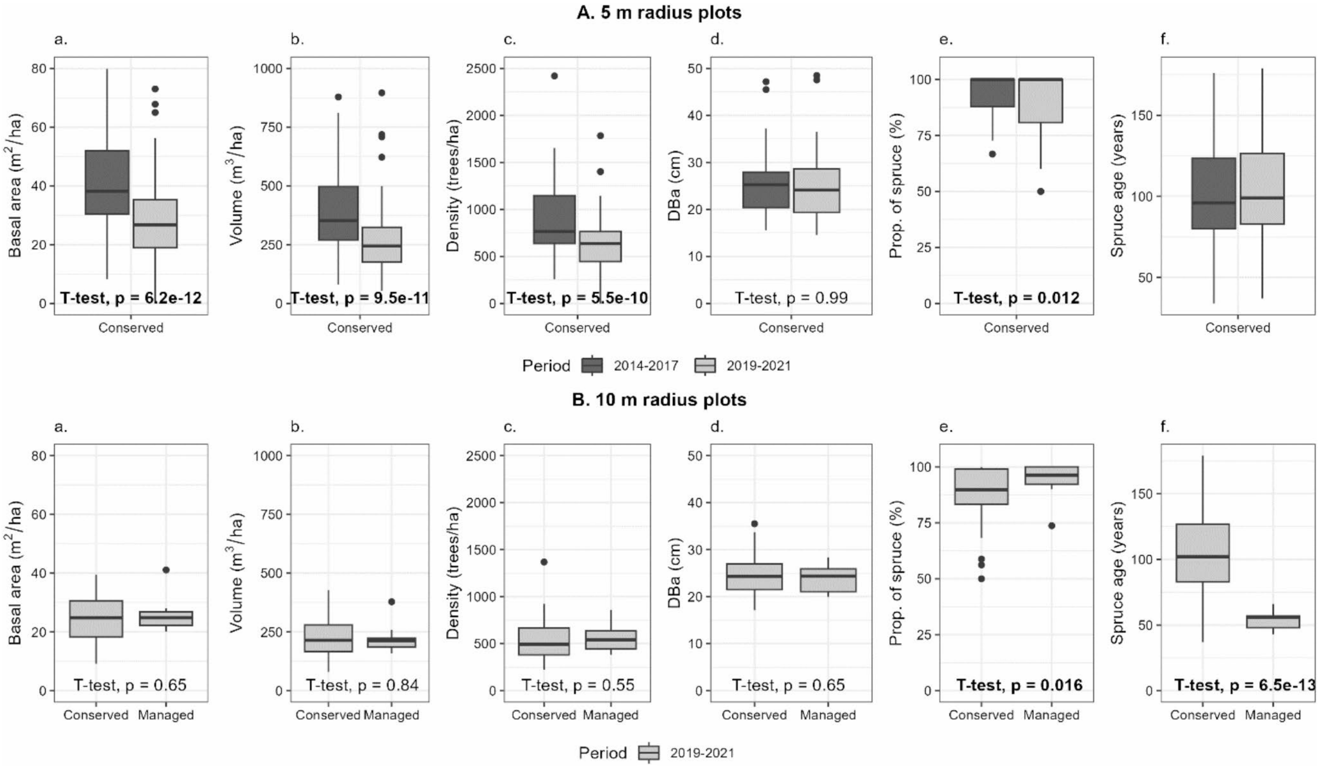

Fig. 4 Stand characteristics of the conserved and managed areas. Subfigures: **a**. Basal area (m^2/ha), **b**. Volume (m^3/ha), **c**. Stand density, **d**. Basal area weighted mean diameter (cm), **e**. The proportion of Norway spruce (%), **f**. The age of Norway spruce (years). The horizontal line inside the boxplot indicates the median value. Error bars represent standard error. In figure A, the *T*-test is for paired data, showing the differences within periods. In figure B, the *T*-test is for unpair data, showing the differences between conserved and managed areas. Figure A. f. does not have a value for *T*-test because of the constant change within periods. The *T*-test values in bold indicate significant results

2024). This was done to meet the needs of practical forestry to identify the damaged stands where sanitation felling should be done. Typically, in boreal conditions in Finland, SBB completes only one generation per year and begins hibernation in August (Annila 1969), but this situation may change under a warming climate. Currently in Finland, sanitation interventions are mainly carried out during winter. Thus, a detection of SBB attack based on tree symptoms and evaluation of the stand damage at the end of the SBB annual cycle would contribute to decision making regarding SBB management (i.e., sanitation felling) and reduce the spreading beetles in the nearby stands, as was also noted by Kautz et al. (2024).

A similar methodology, based on ground-based visual observations of SBB attack symptoms at tree level, was also used earlier by Blomqvist et al. (2018) and Kautz et al. (2023). In addition to the symptoms we assessed, Kautz et al. (2023) considered boring dust as the assessment was done every second week. They found that boring dust is the most accurate symptom for timely detection of infestation in spring or early summer, but not later. When the symptoms are evaluated later in the summer, as was our case in August, the dust is hardly visible as it is spread out by wind and rain.

With the methodology we used, we could not detect the infestations at the tree level in early stages of the SBB attack (i.e., ‘pre-emergence detection’ defined by Kautz et al. 2024) or identify the susceptible trees before the attack. The potential of remote sensing methods combined with machine learning techniques have been studied for the early detection of SBB infestations (e.g., Junttila et al. 2019; Huo et al. 2021) or detection of susceptible trees (e.g., based on water stress Huo et al. 2023; Mandl and Lang 2023). While the remote sensing detection methods have advantages, they currently face practical challenges such as low accuracy and robustness, as well as high costs (Marvasti-Zadeh et al. 2023; Kautz et al. 2024). An early detection in our study was not possible as our study started in 2014 when the trees in the conserved areas were in a more advanced stage of SBB infestation. Despite the limitations of this study, this work is valuable as it detected for the first time the dynamics of SBB infestations and mortality over several years under Finnish conditions.

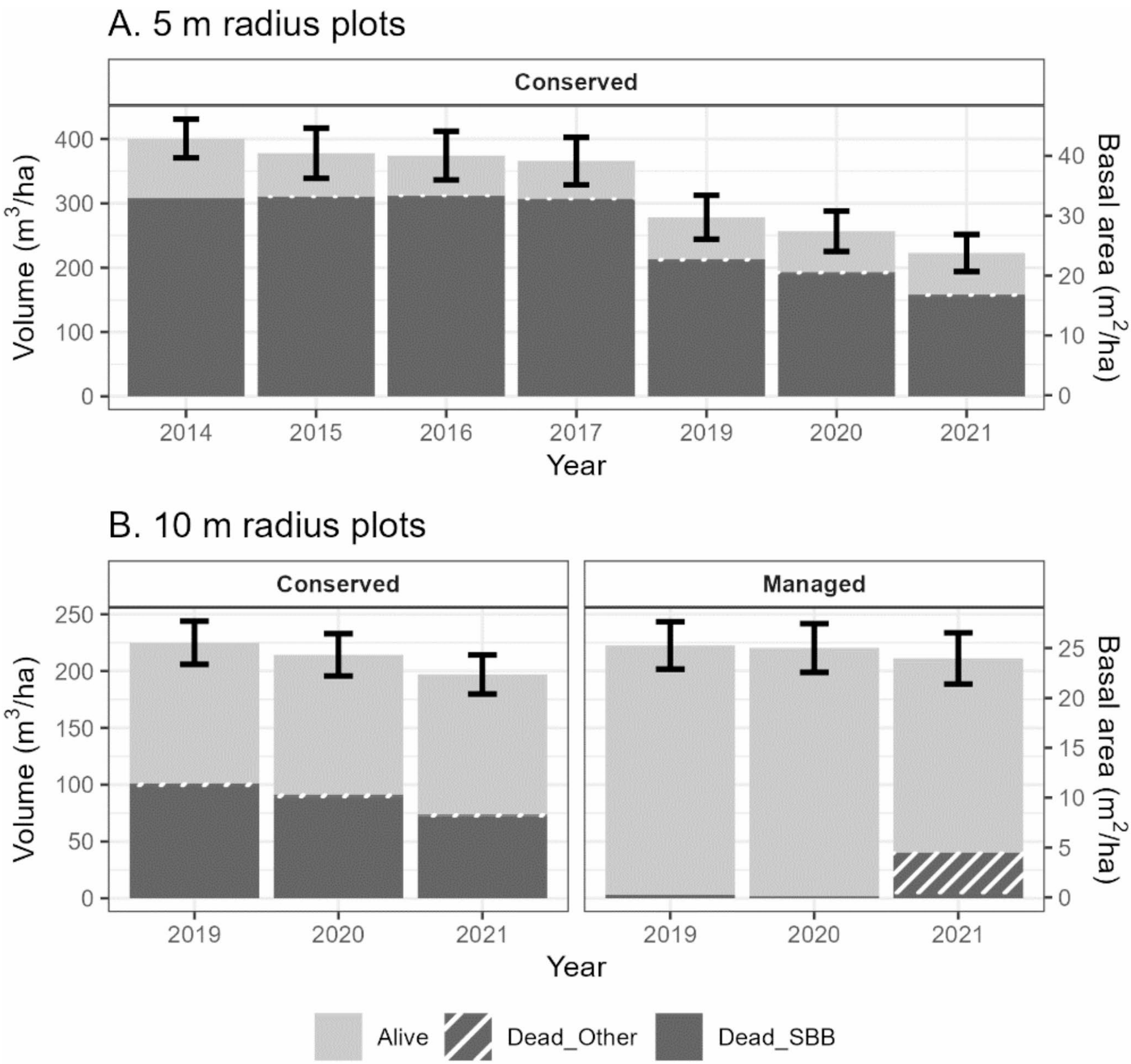

Fig. 5 Development of volume and basal area (±SE) of the standing trees during the study period in plots with a 5-m radius (**A**) in conserved areas and with a 10-m radius (**B**) in conserved and managed areas. The bars of the stand variables show the total basal area and volume, divided between living trees (grey coloured bars), SBB-killed trees (black coloured bars, Dead_SBB), and trees that experienced unidentified mortality (dashed black coloured bars, Dead_Other). The error bars represent standard error

The SBB outbreak in conserved and managed areas

In our study, the SBB outbreak proceeded after a massive wind disturbance caused by two summer thunderstorms in 2010. The attack on standing trees started in 2013, i.e., in the third year after the storm. In 2014, a high percentage of the standing trees were already highly infested. Similarly, Økland et al. (2016) found that the transition of SBB from the fallen trees to the standing trees happened during the third and fourth years after the windfall. The available resources in the nearby area of the windfall and the temperature conditions (e.g., Mezei et al. 2017) further affect the reproductive rate of SBB, followed by the attack and damage of the living trees the following (e.g., Kärvemo et al. 2014) or second summer after the storm (Komonen et al. 2011).

At the time of our assessment (2019–2021), the stands in the conserved areas had significantly higher SBB damage compared to those in managed areas. Likewise, Schroeder and Lindelöw (2002) and Mezei et al. (2017) found a lower tree mortality during an SBB outbreak in managed areas. However, in our case, the initial infestation levels of the stands were not assessed, so the possibility of the conserved and managed stands having a different initial infestation level at the time of our assessment cannot be fully excluded. Regular management may increase the vitality of trees, promoting better adaptation to the site conditions and a lower susceptibility to disturbances (de Groot et al. 2019). Although we found symptoms of highly infested trees in managed areas, the tree mortality rate was lower than that in conserved areas. This may be at least partially explained by a better vitality and a faster recovery capacity of the trees, which was observed by Blomqvist et al. (2018). However, more research is needed to confirm this.

Tree mortality in conserved areas started in the 2nd year after the initial colonization, with the highest increase after the 3rd year. Consequently, a high decrease in standing volume and basal area of living trees was observed 6–7 years after the initial colonisation. Other studies found that the mortality was the highest at the beginning of the outbreak (e.g., Schroeder and Lindelöw 2002; Kärvemo et al. 2014, 2016; Mezei et al. 2017) and then decreased frequently due to host tree depletion (e.g., Mezei et al. 2017). According to Hekkala et al. (2021) and Kärvemo et al. (2017), forest conservation measures, such as the gap-cut method, create a high risk of new SBB attacks after only 5 years. The results of the gap-cut method are similar to those of storm gaps, thus supporting our results.

Potterf et al. (2022) and Sommerfeld et al. (2018) found that managed forests are less resistant to SBB attacks than conserved forests (i.e., natural reserves). This can be explained by the fact that conserved forests may have a higher functional and structural diversity, which increases their resistance and resilience against disturbance agents (Hlásny et al. 2019). Nonetheless, recently established, smaller conservation areas, such as in our study, may also have a lower resistance against SBB compared to larger (and older) nature reserve areas (see e.g., Potterf et al. 2022). Still, differences in forest structure (e.g., age and species composition, stocking), and environmental (climate, site) conditions may explain differences between studies.

The relationship of SBB damage with stand variables

In our study, SBB damage correlated significantly with the basal area of living trees and the age of spruce trees. Kärvemo et al. (2014) and Sproull et al. (2015) found that the basal area of living spruces predicted tree mortality by SBB. However, Sproull et al. (2015) reported that the age of spruce trees did not influence tree mortality caused by SBB. In contrast, other issues related to SBB infestations (i.e., infestation risk in Trubin et al. 2022; individual predisposition in Seidl et al. 2007; and cumulative disturbance in Potterf et al. 2022) were shown to increase significantly with tree age.

Our results showed that SBB damage was independent of tree size (diameter of the host tree), unlike in some previous studies (e.g., Kärvemo et al. 2014; Mezei et al. 2014; Sproull et al. 2015; Korolyova et al. 2022). This may be because the outbreak was in an advanced stage (culmination and retrogradation phase) during most of the study period. Further, year 2015 may represent a culmination of the outbreak in the conserved areas. Yet, the outbreak pattern was patchy over the study area. According to Mezei et al. (2014), for the pre-outbreak to progradation phase and the culmination phase, diameter is an important predictor for tree mortality induced by SBB, but not in the retrogradation phase. Likewise, Sproull et al. (2015) found that the diameter had a low contribution from the progradation to the culmination phase.

In European temperate forests, SBB has damaged large Norway spruce-dominated areas (e.g., Kamińska et al. 2021; Potterf et al. 2022). The increasing amount of susceptible mature Norway spruce in temperate forests has provided favourable conditions for SBB to infest in the past decades (Marini et al. 2017; Hlásny et al. 2021). In our study, the proportion of spruce failed to explain the SBB damage, likely due to the low variation of the spruce proportion in the study area. Typically, in Norway spruce stands, broadleaves are harvested during thinning operations according to 'Best practices for sustainable forest management in Finland' (see https://metsanhoidonsuositukset.fi/en).

Conclusions and future perspectives

Using data from ground-based visual observations, we assessed symptoms for SBB infestation, which provided results about the infestation levels of the trees and the damage of the plots. In conserved areas, 70% of the trees within the 5-m-radius plots were highly infested in the 2nd year (in 2014) after the initial colonization of the standing trees, reaching 90% in the 5th year (2017). Stand-level analysis showed that the conserved areas had significantly higher damage than managed areas during the study period (2019–2021). The variation in SBB damage at the stand level was best explained by the basal area of living trees and the age of spruces. When the SBB damage was analysed separately by each symptom, resinous flows and entrance-exit holes showed similar levels of damage regardless of the year or treatment. Over the course of the outbreak (until 2021), the volume of the stands decreased on average by 80% in conserved areas and 40% in managed areas.

The results of this study demonstrate the potential use of tree-level symptom assessment for the detection of SBB attack and the role of forest management in damaged areas on decreasing the harmful effects of an SBB outbreak at the stand level in managed boreal forests. The ground-based visual assessment of tree symptoms offered a reliable means to evaluate the damage of the stands and could support forest owners and managers in decision making regarding sanitation felling. Such methodology may also support advancement and validation of remote sensing-based detection methods. Additionally, ground-based visual observations of SBB infestation symptoms are inexpensive and only require basic training. Therefore, they could be used to develop applications used for monitoring infestations by forest owners and non-professionals. Such application could help detect SBB infestations to support timely measures and decrease damage in Norway spruce forests.

In addition to response management, more attention should be given to proactive measures that contribute to risk prevention and provide better preparedness for SBB outbreaks in managed forests (EFI 2020; Hlásny et al. 2021). For example, avoiding the cultivation of pure spruce stands, which is still a practice in boreal forests, can help reduce the risk. This is particularly important on forest sites with a relatively low water holding capacity where trees are more susceptible to drought and further SBB outbreaks. Growing mixed forests (admixtures with deciduous species) on suitable sites may also increase forest resilience against SBB outbreaks due to fewer host trees and higher populations of natural enemies (e.g., Kausrud et al. 2012; de Groot and Ogris 2019; Hlásny et al. 2021; Müller et al. 2022). Timely and regular thinning operations to improve tree vigour (outbreak prevention), harvesting of infested trees (sanitation felling and salvage logging), and removal of harvested and wind-damaged trees before swarming of the first annual SBB generation in early summer are necessary risk prevention measures. The use of shorter rotation periods (or lower target diameters) may also enhance forest resilience against SBB outbreaks (e.g., de Groot et al. 2019; Hlásny et al. 2019; Venäläinen et al. 2022). Ultimately, in risk assessment and management, the areas with higher risk of SBB outbreaks and damage should be prioritised.

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Author contributions Design of field experiment (PLS, MK, EH, RN, MPA), field data collection (PLS, MK, MPA), data curation (DCS, PLS, MPA, JT), the design of the study (DCS, PLS, HP, OPT, AK), data visualization and statistics (DCS), writing – original draft preparation (DCS, PLS, HP), writing – review and editing (all authors), funding responsibilities (PLS, HP, EH).

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Data availability The data of this study are available upon request from the corresponding author Diana-Cristina Simon or Docent, Dr. Päivi Lyytikäinen-Saarenmaa.

Code availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

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