



Stand, landscape and climatic attributes contributing to the probability of *Ips typographus* damage in Finland

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ABSTRACT

Large-scale outbreaks of *Ips typographus* L. (SBB) have caused extensive damage to Norway spruce (*Picea abies* (L.) H. Karst.) forests. Under climate change, SBB damage is expected to increase in Northern Europe and especially in Finland, where Norway spruce is one of the most ecologically and economically important tree species. We developed spatially-explicit probability models and SBB damage risk maps using hierarchical logistic regression modelling. We considered various stand, landscape and climatic attributes, including disturbances by routine forestry activities (i.e. new clear-cuts), wind and SBB damage. The analysis drew on detailed, open-access, stand-level forest data collected in 2020–2022 for managed Norway spruce stands in the southern half of Finland (study area), where damage is most prevalent. The study area of 11.4 million ha with more than two million stands Norway spruce stands was split into northern and southern sub-areas to develop sub-area-specific generalised linear mixed effect models for predicting the probability of stand-level SBB damage. We found a generally low probability of SBB damage, higher in the southern sub-area. Landscape attributes showed the strongest effect on SBB damage predisposition, followed by stand and climatic attributes, though the effects differed in sub-areas. The top predictors of SBB damage were proximity to clear-cuts, followed by stand mean diameter at breast height, distance to previous SBB damage and the maximum number of consecutive days with temperature above 25°C. However, careful planning of proactive risk management actions is required, as clear-cuts – including SBB-related salvage loggings – may induce new SBB infestations.

1. Introduction

Over the past few decades, large-scale outbreaks of the European spruce bark beetles (*Ips typographus* L., Coleoptera: Curculionidae) have caused extensive damage to Norway spruce (*Picea abies* (L.) H. Karst.) forests. These outbreaks are the result of various stand, landscape and climatic attributes, which jointly affect bark beetle population dynamics and Norway spruce susceptibility resulting in new damage (Faccoli and Stergulc, 2004). Because climate change is expected to increase *I. typographus* damage and resulting economic losses in the forestry industry (Tikkanen and Lehtonen, 2023; Triviño et al., 2023; Venäläinen et al., 2022), timely assessment and management of damage risks are necessary (de Groot and Ogris, 2019, 2022). Models of damage likelihood may provide valuable support to identify the main drivers of *I. typographus* damage (Blomqvist et al., 2018; de Groot and Ogris, 2022,

2019; Sivrikaya et al., 2022), facilitating the implementation of preventive and responsive forest management measures to mitigate future damage (de Groot and Ogris, 2019; Hlásny et al., 2021; Kuhn et al., 2022).

Stand mean diameter has been reported as important attribute for host selection by *I. typographus*. The thick bark and increased phloem in larger, mature trees provide better conditions for beetle development than younger or slow-growing individuals (Grunwald, 1986; Potterf et al., 2025; Wermelinger, 2004). In turn, landscape attributes such as forest diversity and proximity to recent forest disturbances (e.g. clear-cuts, wind- or beetle-damaged stands) are good predictors of *I. typographus* susceptibility (Eriksson et al., 2007; Klapwijk and Björkman, 2018; Økland et al., 2016; Pulgarín et al., 2024). A high proportion of Norway spruce increases the risk, while a heterogeneous landscape with diversity of forest age structure and tree species reduces

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risk (de Groot et al., 2023, 2019; Klapwijk and Björkman, 2018; Kozhoridze et al., 2024). Wind-damaged stands provide an ideal breeding habitat for beetles increasing the susceptibility of attacks (Økland et al., 2016; Pulgarín et al., 2024) and the formation of damage hotspots “locations where high levels of damage occur” (Pulgarín et al., 2025). Clear-cuts – whether the result of routine forest operations or salvage logging due to wind or beetle damage – can further increase damage susceptibility by creating new forest edges and exposing edge trees to stressing conditions (de Groot and Ogris, 2019; Kautz et al., 2013; Kozhoridze et al., 2024; Stríbrská et al., 2022).

The key climate driver of *I. typographus* population dynamics is air temperature. Until recently, low air temperatures limited its development and voltinism in Finland (Annala, 1969; Doležal and Sehnal, 2007; Økland et al., 2015). Drought is another key driver of bark beetle disturbances, as it weakens the defence of Norway spruce trees against attacks (Nardi et al., 2023; Netherer et al., 2024, 2015; Schiebe et al., 2012). Simultaneous occurrence of high temperatures and dry conditions may lead to rapidly increasing beetle populations, synchronised dispersal flights, mass attacks and severely stressed trees, resulting in serious damage (Netherer et al., 2019; Wermelinger, 2004).

Only a few studies to date have focused on modelling the probability of *I. typographus* damage. This is largely due to methodological constraints in obtaining detailed, location-specific data on infestation and the high computational demands of processing them (Fernández-Carrillo et al., 2024; Nardi et al., 2023; Seidl et al., 2011). Among the few existing studies, de Groot and Ogris (2019) developed an early warning system to predict *I. typographus* damage and support timely interventions; Müller et al. (2022) studied the influence of environmental variables on the forest susceptibility to the beetle damage; Kovárník et al. (2025) examined stand, tree and climate attributes that influence the survival of Norway spruce under *I. typographus* attack; Jönsson et al. (2012) investigated the damage likelihood, whereas Blomqvist et al. (2018) examined the predisposition of an urban forest in southern Finland to *I. typographus* infestations. Besides this last study, previous studies covering southern Finland analysed how stand and landscape attributes affect the number of new damage events (Pulgarín et al., 2024) and the probability of hotspot formation (Pulgarín et al., 2025), although none of these studies were spatially explicit. Assessing how different attributes influence the susceptibility of Norway spruce to *I. typographus* attacks at the margin of its northern distribution limit provides a basis for comparison with conditions in Central Europe, where damage has recently escalated. A national risk model for Finland would therefore complement existing knowledge from Central Europe by highlighting both shared and region-specific risk factors across whole Europe.

Developing nationwide probability models of *I. typographus* damage and identifying the key attributes that contribute to the risk of damage are critical for strengthening forest resilience. This specially applies to boreal regions, where under climate change conditions forests are increasingly vulnerable to insect attacks (Venäläinen et al., 2022). Finland illustrates this need particularly well; the southern half of the country has 11.4 million hectares of forestry land available for wood supply (Korhonen et al., 2021), divided into more than two million stands (Metsäkeskus, 2025). Because this dataset covers the northern limit of the outbreak range for *I. typographus*, it provides a rare opportunity to analyse how stand, landscape and climatic attributes shape the damage likelihood.

Translating knowledge of the attributes affecting *I. typographus* damage into location-specific probability models for risk management in practical forestry has been challenging (Fernández-Carrillo et al., 2024; Nardi et al., 2023; Seidl et al., 2011). As a result, most forest managers react to damage rather than anticipating it. Therefore, probability models capturing the spatial and temporal complexity of *I. typographus* damage are urgently needed to support timely risk management actions (Blomqvist et al., 2018; de Groot and Ogris, 2022, 2019; Sivrikaya et al., 2022), such as the selective removal of infested trees prior to the

emergence of fully developed offspring (Hlásny et al., 2021; Kautz et al., 2013). In this study, we developed spatially-explicit probability models and maps for *I. typographus* damage using data on salvage loggings and hierarchical logistic regression modelling. We considered various stand, landscape and climatic attributes, including disturbances by routine forestry management activities (i.e. new clear-cuts), wind and beetle damage. The analysis drew on detailed, open-access, stand-level forest data collected from 2020 to 2022 of managed Norway spruce stands in the southern half of Finland. The study area was split into northern and southern sub-areas to develop sub-area-specific generalised linear mixed-effect models for predicting the probability of *I. typographus* damage. We hypothesised that the effect of stand, landscape and climatic attributes on the probability of *I. typographus* damage may vary by region. Understanding the relative importance of different attributes to *I. typographus* damage not only helps forest managers plan proactive interventions and strengthen forest resilience but also complements existing knowledge from Central Europe by revealing how risk factors operate at the northern distribution limit.

2. Methods

2.1. Study area

The study area covered the southern half of Finland (up to 64°N; Fig. 1), where *I. typographus* (SBB) damage predominantly occurs within the country. The area comprises 11.4 million ha of forestry land available for wood production, of which 19% is state-owned forests, including managed and protected forests (3.4%; Korhonen et al., 2021). The region is dominated by southern and middle boreal vegetation types, with hemiboreal forests in the southwest and middle boreal forests in central Finland (Ahti et al., 1968). Productive forests in Finland are dominated by *Pinus sylvestris* L. (54%) and Norway spruce (33%), with the remaining area primarily consisting of *Betula pendula* Roth (5.5%) and *Betula pubescens* Ehrh. (5.2%) (Korhonen et al., 2021). The southern half of Finland is mostly lowlands, gradually rising to 200 m above sea level to the northeast (Nygren, 2011).

There is a strong south–north climatic gradient in the study area. During the 1991–2020 climate reference period, the mean annual temperature ranged from 6.0°C in the south (Helsinki, latitude 60.2°N) to 2.6°C in the north (Kajaani, latitude 64.2°N), and annual precipitation ranged from 680 mm in Helsinki to 585 mm in Kajaani (Finnish Meteorological Institute, 2022). The wide range of ecological conditions in the study area provides a robust setting for identifying the drivers of SBB damage at its northern distribution limit.

Due to limitations identified during statistical modelling, specifically overdispersion, the study area, which comprised Finnish regions — administrative zones (regions) given by the Metsäkeskus — with more than five SBB-damaged stands during 2020–2022, was split into two sub-areas based on the amount of SBB-damaged stands, one representing the southern part of the study area (green area in Fig. 1) and the other representing the northern part (blue area Fig. 1). Fig. 2 depicts the number of damaged and undamaged stands by region. More information on this grouping is provided in Section 2.3.

2.2. Datasets

We used two publicly available spatial datasets, containing information on privately-owned forests, which accounts for 78% of the forestry land area available for wood production (Korhonen et al., 2021). These datasets are collected and distributed by the Finnish Forest Centre (Metsäkeskus), the state authority for forestry administration in Finland. The first dataset was comprised of mandatory forest-use notifications submitted by forest owners (metsänkäyttöilmoitukset), documenting salvage logging intentions due to wind and SBB damage (Metsäkeskus, 2025). This is the only comprehensive, spatially-explicit dataset on salvage logging in Finland that identifies areas — whole

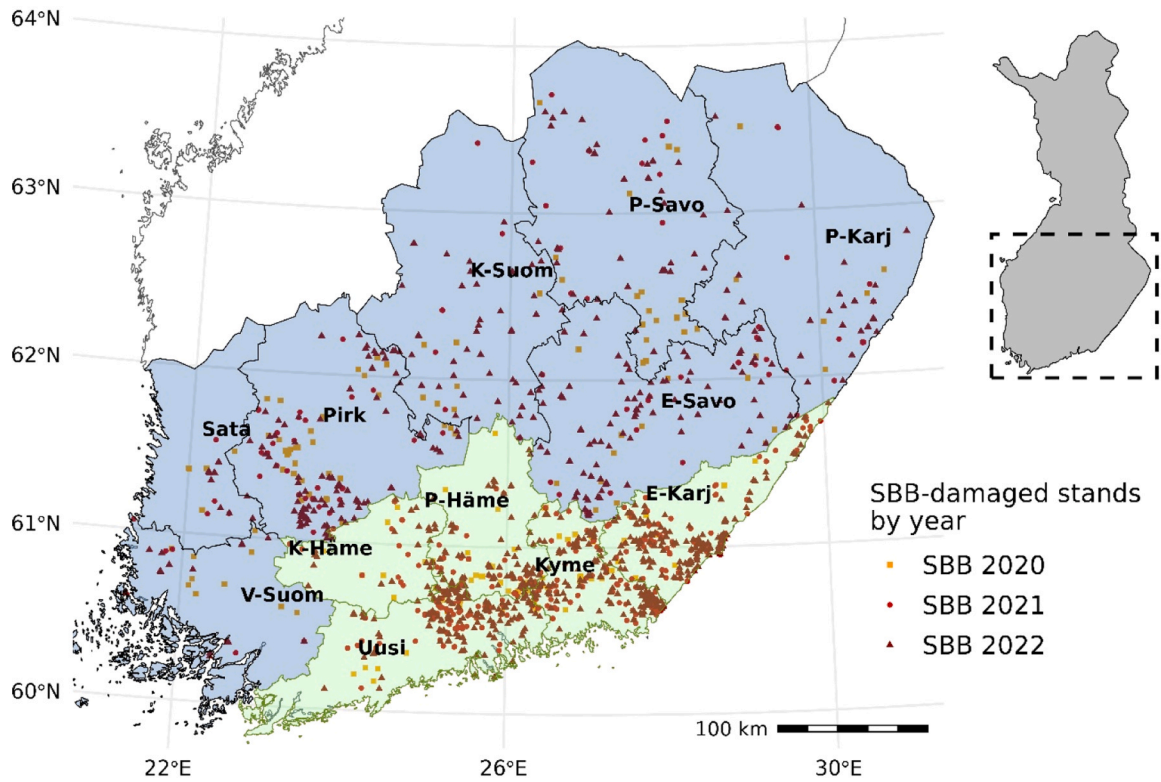


Fig. 1. Study area (southern half of Finland) with regions reporting *Ips typographus* (SBB) damage to Norway spruce based on data from 2020 to 2022. The study area was split in two areas for modelling purposes: a southern area (in green) comprised of Etelä-Karjala (E-Karj), Kanta-Häme (K-Häme), Kymenlaakso (Kyme), Päijät-Häme (P-Häme) and Uusimaa (Uusi) and a northern area (in blue) comprised of Etelä-Savo (E-Savo), Keski-Suomi (K-Suom), Pirkanmaa (Pirk), Pohjois-Karjala (P-Karj), Pohjois-Savo (P-Savo), Satakunta (Sata) and Varsinais-Suomi (Vars).

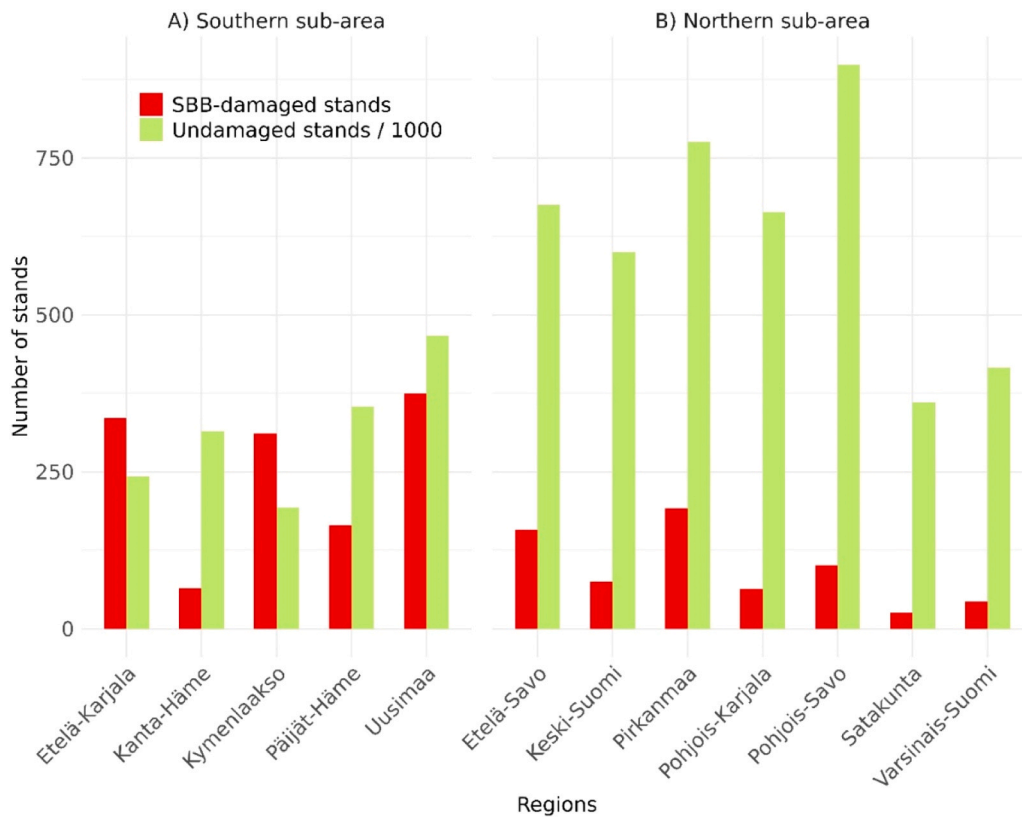


Fig. 2. Norway spruce stands damaged by *Ips typographus* (SBB) or free of damage in (A) southern and (B) northern sub-areas from 2020 to 2022. Note that the number of undamaged stands should be multiplied by 1000. The numbers of SBB-damaged stands are based on salvage logging reports.

stands or partial cuts — harvested in response to SBB damage, the standard practice for managing such damage. We used these reports as proxies for wind and SBB damage at stand level, with the limitation that this dataset does not provide information on the volumes of damaged timber or the number of affected trees. The second dataset contains stand-level details about forest structure, obtained through remote sensing and field assessments (Metsäkeskus, 2025). In these datasets, the average stand size is 1.4 ha (Metsäkeskus, 2021).

We downloaded the forest-use notification data on 26 June 2023, removing duplicated notifications and selecting Norway-spruce-dominated stands intended to be logged because of wind and SBB damage (Section A in Fig. 3), or labelled as ‘insect damage’ during 2020–2022. We included the ‘insect damage’ label because SBB may have been recorded under this term; to the best of our knowledge, very few cases exist in Finland where insects other than SBB could cause enough damage to necessitate salvage logging. From this dataset we also identified all other clear-cuts in ‘healthy’ Norway spruce stands — stands not reported as damaged by SBB or other insects, as described above. These stands help us identify Norway spruce stands which were potentially susceptible for SBB but not attacked and still harvested (Section A in Fig. 3).

To determine the most probable year of SBB damage occurrence, SBB damage was attributed to the report year if the report was made between June and December, but to the previous calendar year if the report was made between January and May, following Netherer et al. (2019) and Müller et al. (2022). Wind damage reports made from January to August were assigned to the same calendar year, while reports from September to December were assigned the following year, because SBB hibernate from autumn to early spring. This approach aligns the presence of wind damage with the beetle’s swarming/reproduction period (Pulgarín et al., 2024).

On 18 November 2021, we downloaded the forest structure dataset to identify living (not harvested) Norway spruce stands that were potentially susceptible to SBB. Forest structure data for previous years needed to match with forest-use notifications from previous years (i.e. 2012–2019) were not available. We first removed duplicated stands, selecting the calculated data and Norway spruce as the primary tree species. Next, we selected the Norway spruce stands susceptible to SBB damage, defined as stands having a stand mean diameter at breast height (Dmean) greater than 15 cm and a mean age greater than 25 years in 2021. These limits are typical for Norway spruce stands in which SBB damage is expected in Finland (Pulgarín et al., 2024). From the forest structure dataset, we discarded unrealistic Dmean values (greater than 100 cm), as well as stands with an area less than 256 m², which is smaller than the resolution of the remote sensing methods used by Metsäkeskus (16 × 16 m grid; Metsäkeskus, 2025), and inventory and quality assurance data came from 9 m radius plots (254.5 m²; Metsäkeskus, 2025).

To identify recent clear-cuts that were potential drivers of SBB damage – due to their creation of edges in nearby Norway spruce stands (Kautz et al., 2013; Stříbrská et al., 2022) – we downloaded the forest structure dataset again on 3 January 2024 and selected stands less than five years old during the sample period (2020–2022) based on the most recent age data. The resulting datasets constructed using information from the forest-use notifications and forest structure define the susceptible Norway spruce stands (including healthy stands that were already cut) and SBB-damaged stands for each analysed year (2020–2022), as depicted in Section C of Fig. 3.

To examine the attributes affecting the probability of SBB damage at the stand level, we supplemented our constructed datasets with one stand, seven landscape and six climatic predictors (Section B of Fig. 3), summarised in Table 1. The stand-level predictor was Dmean, obtained

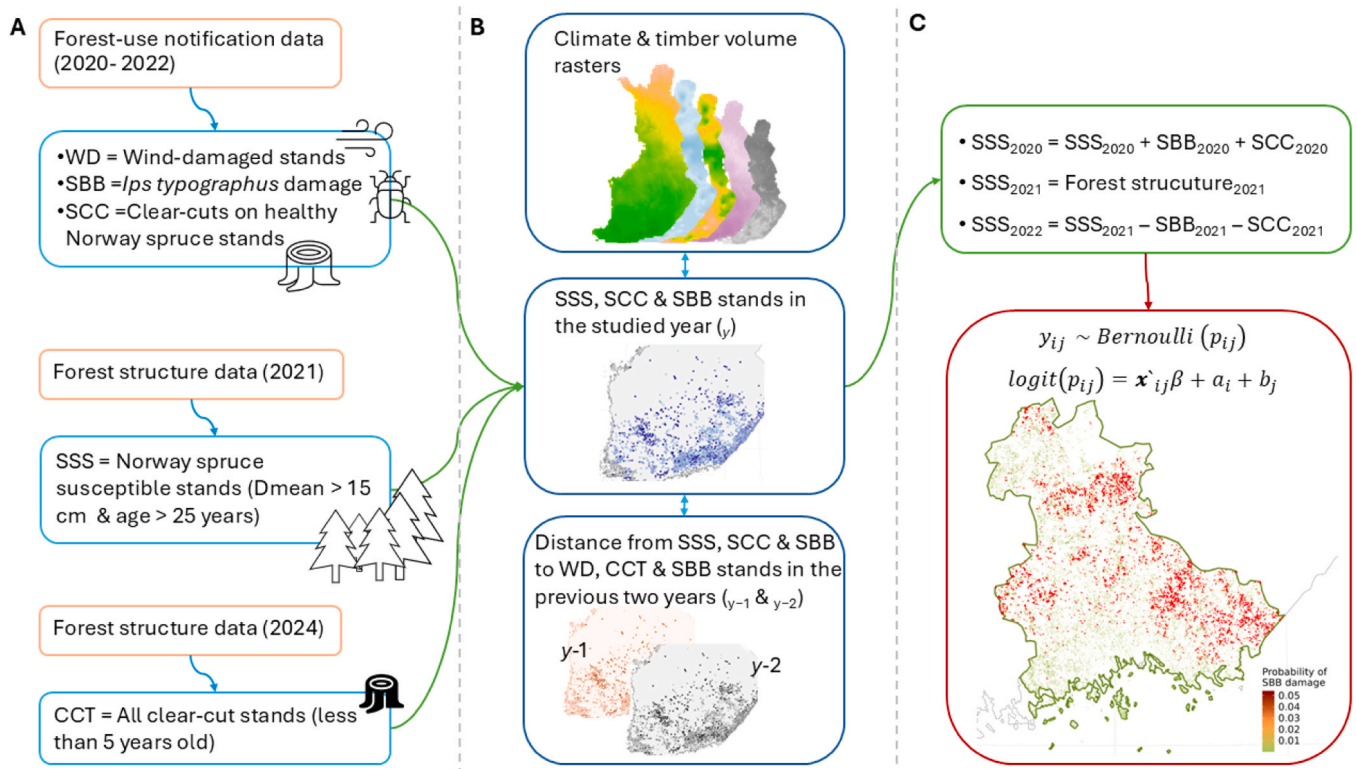


Fig. 3. Flow chart of the methodology for assessing the probability of *Ips typographus* (SBB) damage in Finland based on data from 2020 to 2022. The analysis includes (A) dataset compilation based on forest-use notifications and forest structure data; (B) the addition of landscape (i.e. distance to previous disturbances and volume) and climatic attributes; and (C) the identification of SSS – including SSS, SBB and SCC – for each analysed year (2020–2022) and the development of a probabilistic model, illustrated with an example map showing the predicted stand-level probability of SBB damage on susceptible Norway spruce stands. This map demonstrates the model’s practical utility for targeted management interventions.

Table 1

Summary of forest stand, landscape and climatic attributes for Norway spruce stands (either damaged or not, but susceptible) used in *Ips typographus* (SBB) damage probability assessment in Finland (2020–2022). Climatic predictors represent the period from May to August.

Attribute	Type	Range in the southern sub-area (mean)	Range in the northern sub-area (mean)
Stand mean diameter at breast height (cm)	Stand	15–57.2 (24.5)	15–96 (23.6)
Distance to previous WD _{y-1} (km)	Landscape	0–60.6 (9.5)	0–54.4 (6.2)
Distance to previous WD _{y-2} (km)	Landscape	0–60.6 (10.9)	0–94.2 (8.8)
Distance to previous SBB damage _{y-1} (km)	Landscape	0–84.6 (12.9)	0–128.1 (21.9)
Distance to previous SBB damage _{y-2} (km)	Landscape	0–84.6 (15.2)	0–131.1 (26.8)
Distance to previous clear-cuts (km)	Landscape	0–12.8 (0.5)	0–25.7 (0.4)
Volume of Norway spruce for 2021 (m ³ /ha)	Landscape	4.3–361.1 (68.1)	0.4–561.4 (62.9)
Volume of tree species other than Norway spruce for 2021 (m ³ /ha)	Landscape	15.4–183.5 (85.6)	1.6–195.2 (83.7)
Precipitation _{y-1} (mm)	Climate	118.1–373.9 (254.1)	137.3–374 (246.9)
Precipitation _y (mm)	Climate	96.1–373.9 (248)	111.5–374 (260)
Maximum number of consecutive hot days _{y-1} (n)	Climate	0–8 (1.3)	0–7 (0.7)
Maximum number of consecutive hot days _y (n)	Climate	0–8 (1.4)	0–7 (0.7)
Cumulative thermal sum _{y-1} (GDD)	Climate	991–1508 (1244)	878–1438 (1173)
Cumulative thermal sum _y (GDD)	Climate	1020–1508 (1270)	938–1438 (1208)

Note: WD = wind damage; GDD = growing degree days. Attributes for the previous two years are denoted by the subscripts $y - 1$ and $y - 2$, respectively.

from the forest structure and forest-use datasets. Five of the landscape attributes represented the Euclidean distance from the SBB-damaged and susceptible Norway spruce stands (target stands) to the nearest wind- or SBB-damaged stands in the previous two years ($y - 1$ and $y - 2$), as well as to the nearest clear-cut. These distances were calculated using the centroids of the stands. The sixth landscape attribute was the volume of all Norway spruce stands in a 500 m buffer zone around each target stand during 2021. To calculate this attribute, we used multi-source National Forest Inventory data from 2021, provided by the Natural Resources Institute Finland (LUKE, 2024) which we downloaded on 8 March 2024. The volume data for Norway spruce and the total volume of all tree species came in raster format with a spatial resolution of 16×16 m. To determine the volume of all other tree species excluding Norway spruce, we subtracted the volume of Norway spruce from the total volume. It served as the seventh and final landscape attribute. We estimated all volumes by averaging the values of the raster cells intersecting each buffer, weighted by the proportion of the cell area covered.

The climatic attributes, measured from May to August, included the annual maximum consecutive number of hot days (i.e. days with maximum temperature above 25°C), total precipitation and cumulative thermal sum above a 5°C threshold (Annala, 1969). The annual maximum number of consecutive hot days (as a proxy for heat wave severity) may reflect an increased potential for SBB damage, as such temperatures fall within the beetle's optimal range for flight activity, dispersal and development. With temperatures above 25°C, the frequency and distance of the beetle's flight increase (Funke and Petershagen, 1994; Hinze and John, 2019) and oviposition and population growth reach their maximum (Grodzki et al., 2006; Wermelinger and Seifert, 1999). These conditions can compress emergence timing and, by increasing the number of simultaneously active individuals, promote synchronised dispersal flights and mass attacks – a key mechanism for overcoming host tree defences (Wermelinger, 2004). The three climatic predictors were calculated for both the current year (y) and the previous year ($y - 1$) and were extracted from climate rasters provided by the Finnish Meteorological Institute using the target stands' centroid. The climate

rasters were created using the FMIClimGrid dataset (Aalto et al., 2016), which provides daily temperature and precipitation data at a $1 \text{ km} \times 1 \text{ km}$ resolution. This dataset is based on the observations by the Finnish Meteorological Institute and the European Climate Assessment & Dataset (Klok and Klein Tank, 2009), using a gridding process that employed kriging interpolation and incorporated inputs such as station coordinates (latitude and longitude), topography and proximity to water bodies.

The final dataset included 14 attributes: one stand-level, seven landscape-level and six climate-related (Table 1). Unlike the datasets used in earlier studies (Pulgarín et al., 2025, 2024), this dataset incorporates recently observed SBB damage not previously analysed. It also includes broad-scale coverage of infestation and non-infestation records with precise stand-level geolocation and includes climatic attributes which were not considered in the mentioned studies covering Finland.

2.3. Data analysis

We used binary generalised linear mixed-effect models (GLMMs) with a logit link function to study the effects of the selected attributes (Table 1) on the probability of SBB damage. To fit the GLMMs, we considered the grouping and unbalanced structure of the data by defining random effects according to the region and the year of the damage, following Eq. 1,

$$y_{ij} \sim \text{Bernoulli}(p_{ij})$$

$$\text{logit}(p_{ij}) = \mathbf{x}_{ij}^T \beta + a_i + b_j \quad (1)$$

where, y_{ij} is a binary indicator equal to 1 if the stand is SBB damaged and 0 otherwise; p_{ij} is the probability of SBB damage in region i during year j ; $\mathbf{x}_{ij}^T \beta$ are the fixed predictors (Table 1) and the corresponding coefficient vector β ; a_i region and b_j year are the normally distributed random effects with means of zero and constant variances. Models of this kind

provide a useful framework for assessing the relationship between predictor attributes and the probability of SBB damage ($\alpha = 0.05$; Diaz-Quijano (2016).

The distribution of SBB damage, as shown in Fig. 1, suggests a deterministic process driving the aggregation of damage in certain favourable locations. Previous research has demonstrated that SBB-damaged stands exhibit both spatial and temporal autocorrelation (Potterf et al., 2025; Pulgarín et al., 2025), suggesting that they are not independent (Siabato and Guzmán-Manrique, 2019). This dependence potentially results in under- or overdispersed models (Mehtätalo and Lappi, 2020; Morales and López, 2009) and can lead to biased parameter significance, incorrect or overly complex models and imprecise predictions (Morales and López, 2009; Morales and Lozano, 2014).

Our preliminary model, a single model for the entire study area, led to overdispersion 2.304, according to the dispersion statistic defined as Pearson X^2 divided by the degrees of freedom of the residuals (Hardin and Hilbe, 2007; Hilbe, 2009). To account for this overdispersion and obtain a well-fitted model, we included year and region random effects and divided the study area into two contiguous sub-areas, as mentioned at the end of Section 2.1. The first sub-area included the southern regions Kymenlaakso, Kanta-Häme, Uusimaa, Etelä-Karjala and Päijät-Häme (Fig. 1 & Fig. 2). The second sub-area included the regions Pirkanmaa, Pohjois-Karjala, Keski-Suomi, Pohjois-Savo, Varsinais-Suomi, Etelä-Savo and Satakunta in the north of the study area (Fig. 1 & Fig. 2). The regions with the most SBB damage reports and hotspots from 2020 to 2022 are within the southern sub-area (Pulgarín et al., 2025).

We assessed collinearity among predictors using the variance inflation factor (VIF), which indicates whether a predictor has a strong linear relationship to others, potentially reducing model stability and interpretability (Sikkink et al., 2007). Although multicollinearity does not violate model assumptions (Mehtätalo and Lappi, 2020), VIF values above 10 are generally considered problematic, though stricter thresholds have also been proposed (Chatterjee and Hadi, 2012; Montgomery et al., 2012; Sikkink et al., 2007). Some predictors showed moderate collinearity (see supplementary material, Table S. 1), but all were

retained due to their ecological relevance to SBB damage distribution. We acknowledge the limitations in isolating their individual effects in Section 4. Finally, we evaluated the model’s performance by calculating the area under the receiver operating characteristic curve (AUC) – sensitivity (fraction of correctly classified positive responses) against 1 - specificity (proportion of correctly classified negative responses) (Faraway, 2016; Martínez-Cambor, 2007).

Model fit was assessed according to overdispersion (i.e. dispersion statistic) and temporal autocorrelation (Durbin-Watson test over standardised simulated residuals). Because the response is spatially distributed (probability of SBB damage at stand level), we tested for residual spatial autocorrelation using the sample variogram to be sure that spatial dependence was accounted for. For statistical analysis, we used RStudio v.2023.12.0 + 369 (RStudio Team, 2023) with the following packages: Simple Features ‘sf’ version 1.0–5 (Pebesma, 2018) for the geographical analysis; ‘exactextractr’ version 0.10.0 (Baston, 2024) to extract data from the climate and volume rasters; ‘glmmTMB’ version 1.1.7 (Brooks et al., 2017) to develop the GLMMs and to calculate probabilities; ‘DHARMA’ version 0.4.7 (Hartig, 2024) to obtain standardised simulated residuals; ‘gstat’ version 2.1–2 (Gräler et al., 2016) to calculate the sample variogram, and ‘performance’ version 0.12.4 (Lüdecke et al., 2021) to compute the coefficients of determination of the models following Nakagawa et al., (2017).

3. Results

The two GLMMs predicting the probability of SBB damage in Norway spruce stands in the southern and northern sub-areas provided an adequate and realistic fit to the data. They showed no signs of significant under- or overdispersion or spatial or temporal autocorrelation (Table 2 & Fig. S. 1). Most of the random variation occurred at the year level, especially in the southern sub-area, indicating the probability of SBB damage varied more with year than with region, which also had less variation in the northern area. The model for the southern sub-area explained 65.6 % of data variability (conditional R^2), with 54.4 %

Table 2

Summary of the generalised linear mixed-effects models for the southern and northern sub-areas, indicating the effects of 14 covariates on the probability of *Ips typographus* (SBB) damage in Norway spruce stands during 2020–2022.

	Southern sub-area				Northern sub-area			
Fixed effects								
Parameter	Estimate	Std. Error	z value	Pr(> z)	Estimate	Std. Error	z value	Pr(> z)
Intercept	-9.825	1.929	-5.092	< 0.001	-4.957	2.163	-2.292	0.022
Stand mean diameter at breast height (Dmean)	0.155	0.006	27.205	< 0.001	0.140	0.006	21.668	< 0.001
Distance to WD _{y-1}	-0.015	0.007	-2.108	0.035	-0.006	0.011	-0.572	0.567
Distance to WD _{y-2}	-0.033	0.007	-4.966	< 0.001	0.016	0.007	2.328	0.020
Distance to SBB _{y-1}	-0.090	0.007	-12.236	< 0.001	-0.042	0.005	-9.012	< 0.001
Distance to SBB _{y-2}	-0.030	0.005	-5.922	< 0.001	-0.015	0.004	-4.153	< 0.001
Distance to clear-cut	-2.190	0.165	-13.297	< 0.001	-0.555	0.155	-3.585	< 0.001
Volume of Norway spruce	0.002	0.001	2.010	0.045	-0.003	0.002	-1.817	0.069
Volume of tree species other than Norway spruce	-0.024	0.002	-10.570	< 0.001	-0.017	0.003	-5.653	< 0.001
Precipitation _{y-1}	-0.008	0.002	-4.366	< 0.001	-3.0e-4	0.002	-0.170	0.865
Precipitation _y	-0.004	0.002	-2.343	0.019	-0.005	0.002	-2.868	0.004
Maximum number of consecutive hot days _{y-1}	-0.068	0.031	-2.184	0.029	0.015	0.043	0.341	0.733
Maximum number of consecutive hot days _y	-0.048	0.038	-1.255	0.209	0.126	0.064	1.978	0.048
Thermal sum _{y-1}	0.002	0.002	1.343	0.179	-0.000091	0.002	-0.040	0.968
Thermal sum _y	0.002	0.002	1.033	0.302	-0.003	0.002	-1.315	0.189
Random effects								
Parameter		Variance	Std.Dev.	Groups		Variance	Std.Dev.	Groups
Year	Intercept	0.608	0.780	3	Intercept	0.198	0.445	3
Region	Intercept	0.458	0.676	5	Intercept	0.049	0.222	7
Model evaluation								
Dispersion statistic	1.088				0.912			
Temporal autocorrelation (Durbin-Watson)	1.929	p-value	0.9545		1.05	p-value	0.198	
Number of observations	1572,069				4389,654			
Marginal R^2	0.544				0.251			
Conditional R^2	0.656				0.303			
Area under the receiver operating characteristic curve (AUC)	0.889				0.810			

Note: WD = nearest wind-damaged stand; SBB = nearest SBB-damaged stand. Predictors for the previous two years are denoted by the subscripts $y - 1$ and $y - 2$, respectively.

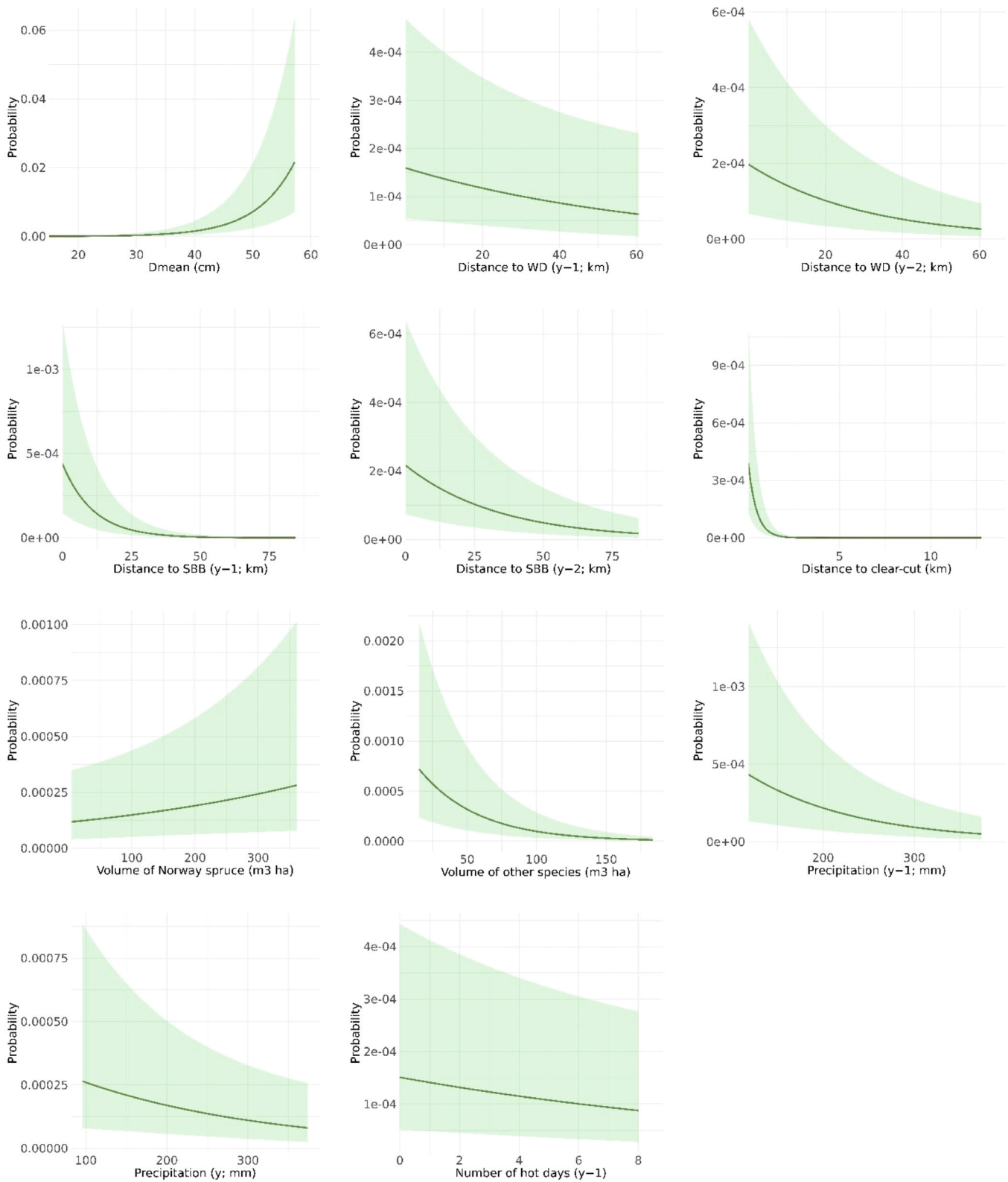


Fig. 4. Estimated probability of *Ips typographus* (SBB) damage to a given Norway spruce stand using the model for the southern sub-area and the fixed effects for each statistically significant predictor, holding other predictors at their mean. Please note the different x- and y-axis scales for each plot, also when comparing plots between sub-areas for each variable. Dmean = forest stand mean diameter at breast height; WD = nearest wind-damaged stand. Predictors for the previous two years are denoted by the subscripts $y - 1$ and $y - 2$, respectively. The shaded areas represent the 95 % confidence intervals.

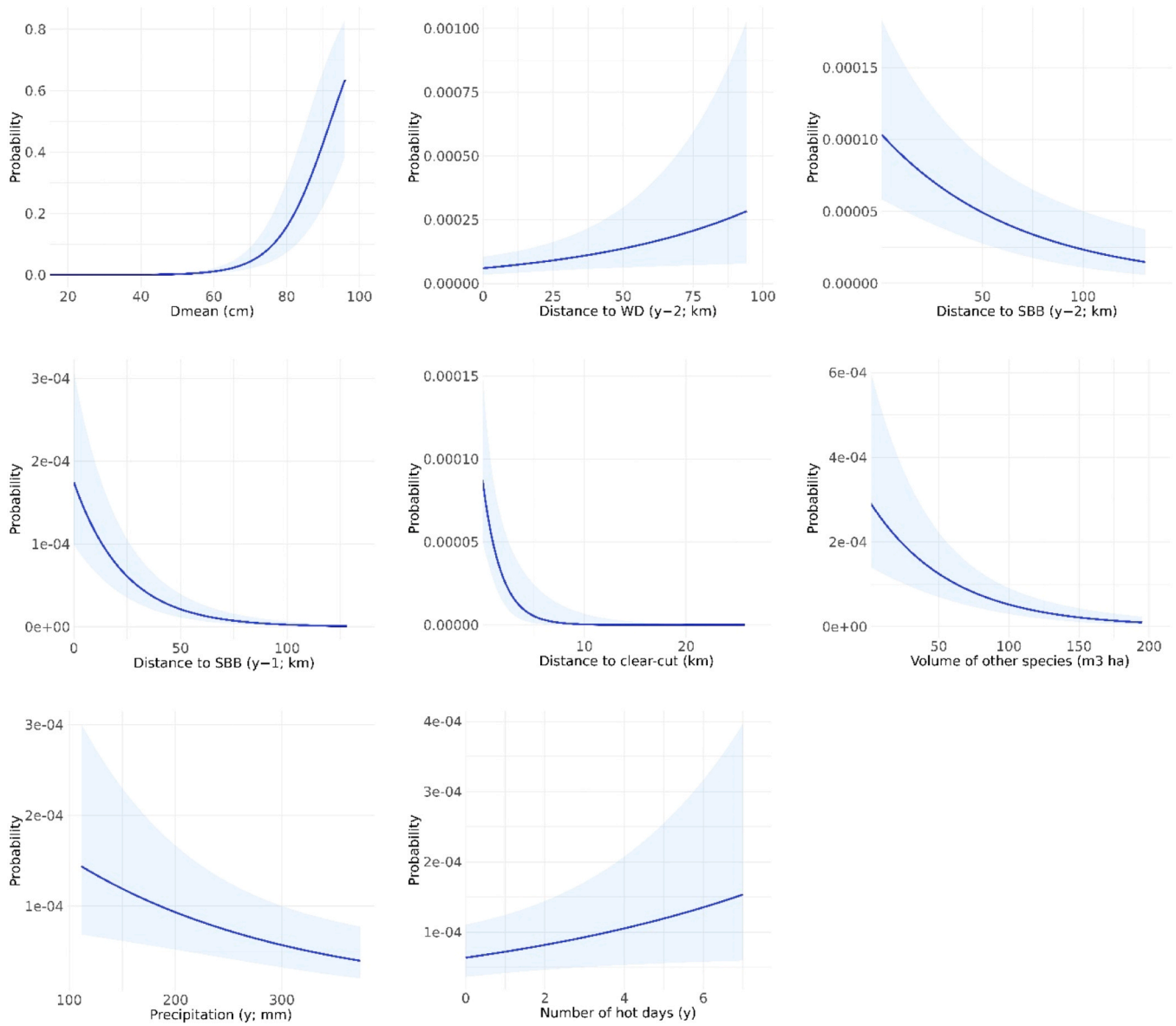


Fig. 5. Estimated probability of *Ips typographus* (SBB) damage to a given Norway spruce stand using the model for the northern sub-area and the fixed effects for each statistically significant predictor, holding other predictors at their mean. Please note the different x- and y-axis scales for each plot, also when comparing plots between sub-areas for each variable. Dmean = forest stand mean diameter at breast height; WD = nearest wind-damaged stand. Predictors for the previous two years are denoted by the subscripts $y - 1$ and $y - 2$, respectively. The shaded areas represent the 95 % confidence intervals.

explained by fixed effects and 11.2 % by random effects (Table 2). In contrast, the model for the northern sub-area explained only 30.3 % of data variability (conditional R^2), with 25.1 % explained by fixed effects and 5.2 % explained by random effects. AUC values higher than 0.81 (Table 2) verified that the models are well fitted and demonstrate strong predictive accuracy across both sub-areas.

During the study period, the probability of SBB damage was low, ranging from 0 to 0.125 (mean = 0.00034). The mean probability of damage in the northern and southern sub-areas was 0.00012 and 0.00058, respectively. Most of the assessed attributes had very limited effects on the probability of SBB damage, with the exception of distance to clear-cuts and Dmean. In the northern sub-area, the maximum number of consecutive hot days during the current year also had a substantial effect on the probability of SBB damage (Table 2, Fig. 4 & Fig. 5).

The shorter the distance to clear-cuts, the higher the probability of damage, with amplified effects in the northern sub-area (Fig. 4 & Fig. 5). Interestingly, the probability of SBB damage decreased sharply with increasing distance from clear-cuts, with the highest probabilities

observed at very short distances (<0.5 km; Fig. 4 & Fig. 5). As Dmean increased, the probability of SBB damage also increased in both sub-areas (Fig. 4 & Fig. 5). An increase in the volume of Norway spruce in the surrounding landscape also raised the probability of SBB damage in the southern sub-area, although the effect was very small. In the northern sub-area, the probability of SBB damage increased when the maximum number of consecutive hot days during the current year increased and when the distance to the closest wind-damaged stand from two years prior (WD_{y-2}) increased. All other statistically significant predictors had a negative impact on the probability of SBB damage. It is interesting to note that WD_{y-2} presented a contrasting effect on the susceptibility to SBB damage ($p < 0.05$); the susceptibility of a stand to SBB damage increased in the south sub-area when its distance to a 2-year old wind damaged stand decreased, but stand susceptibility to SBB damage decreased in the northern sub-area when distance to a 2-year old wind damaged stand decreased. However, WD_{y-2} was the only variable presenting such contrast.

The stand-level probabilities of SBB damage for each region in 2022

Table 3

Predicted probability of *Ips typographus* (SBB) damage in Norway spruce stands in the upper decile in 2022 by region. The maximum value in each range represents the highest predicted probability within a given region.

Region	Sub-area	SBB damage probability for upper decile		Count of stands in the upper decile
		Range	Mean	
Etelä-Savo	Northern	0.0010 – 0.0178	0.0015	21,517
Keski-Suomi	Northern	0.0005 – 0.0066	0.0009	19,225
Pirkanmaa	Northern	0.0008 – 0.0443	0.0013	25,136
Pohjois-Karjala	Northern	0.0004 – 0.0067	0.0007	21,347
Pohjois-Savo	Northern	0.0005 – 0.0247	0.0007	28,966
Satakunta	Northern	0.0003 – 0.0064	0.0005	11,703
Varsinais-Suomi	Northern	0.0004 – 0.0047	0.0006	13,534
Etelä-Karjala	Southern	0.0056 – 0.0876	0.0099	7626
Kanta-Häme	Southern	0.0007 – 0.0159	0.0015	10,185
Kymenlaakso	Southern	0.0065 – 0.0992	0.0117	6141
Päijät-Häme	Southern	0.0019 – 0.1033	0.0040	11,431
Uusimaa	Southern	0.0036 – 0.1811	0.0090	15,142

were generally low, reaching up to 0.181 in the southern sub-area, in Uusimaa (Table 3, Fig. 6 & Fig. 7) and up to 0.044 in the northern sub-area, in Pirkanmaa. As reflected in the map in Fig. 6 and in the estimated probabilities displayed in Fig. 4 and Fig. 5, the regions in the southern sub-area had higher probability of beetle damage than regions in the northern sub-area. Fig. 7 presents a small area from Uusimaa, depicting the spatial distribution of the considered forest disturbances (i.e. wind-, SBB-damaged stands and other clear-cuts) and the estimated probability of damage to susceptible Norway spruce stands. This map clearly shows the complex spatial distribution between the studied disturbances, as indicated by the developed models and the susceptible Norway spruce stands with a higher probability of damage near clear-cuts.

4. Discussion

In this study, we developed spatially-explicit probability models and maps of SBB damage probability in Norway spruce stands using

hierarchical logistic regression modelling, considering various stand, landscape and climatic attributes — including disturbances by routine forestry activities (i.e. new clear-cuts), wind and SBB damage. We used detailed, open-access, stand-level forest data collected during 2020–2022 for managed Norway spruce stands in the southern half of Finland, located at the northern margin of the area where the species is known to cause important commercial damage in Europe. The fitted models produced realistic estimates and predictions, supporting the identification of key attributes for stands where damage is most likely to occur. In general, our results indicate that stand mean diameter and the proximity to clear-cuts are the strongest drivers of SBB damage likelihood at the stand level. Also, our results indicate highest likelihood in the southern sub-area, probably as a result of higher population levels in the area, mechanism demonstrated in previous research (Faccoli and Stergulc, 2004). Some unexplained variability remains in the data, however, particularly in the northern sub-area. Our findings provide support for evidence-based proactive risk management of SBB damage.

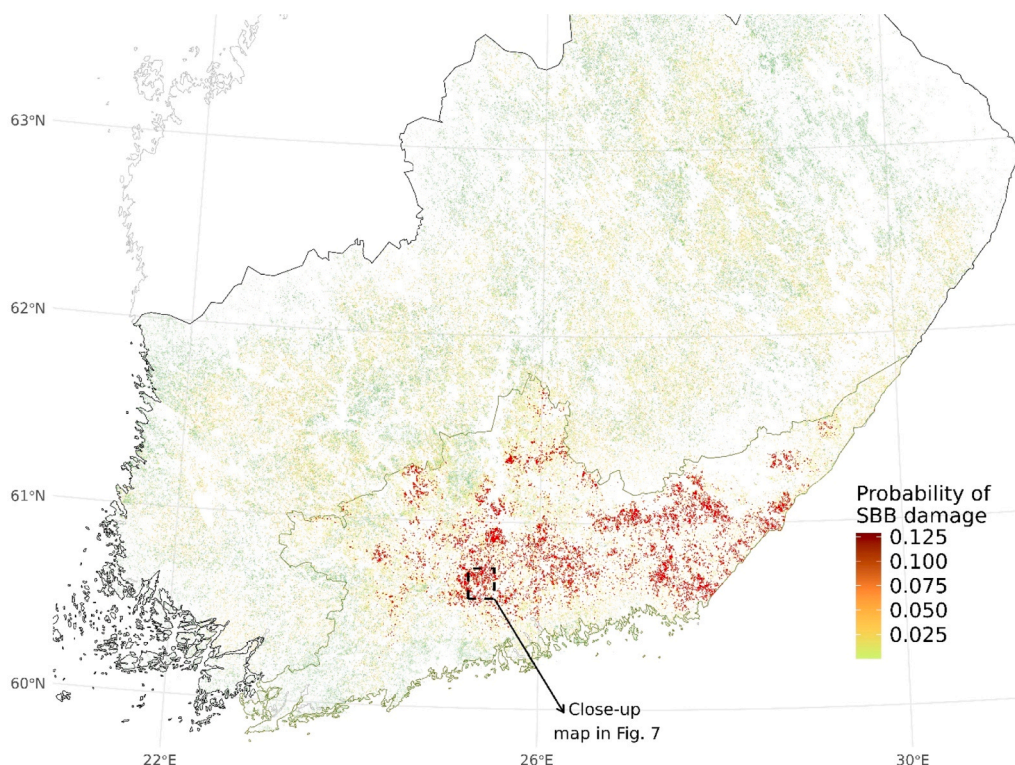


Fig. 6. Predicted probability of *Ips typographus* (SBB) damage in Norway spruce stands in southern and northern sub-areas, in 2022. Colour intensity indicates the predicted probability, with most stands showing low values. The top 1 % of stands with higher probabilities are presented in dark red.

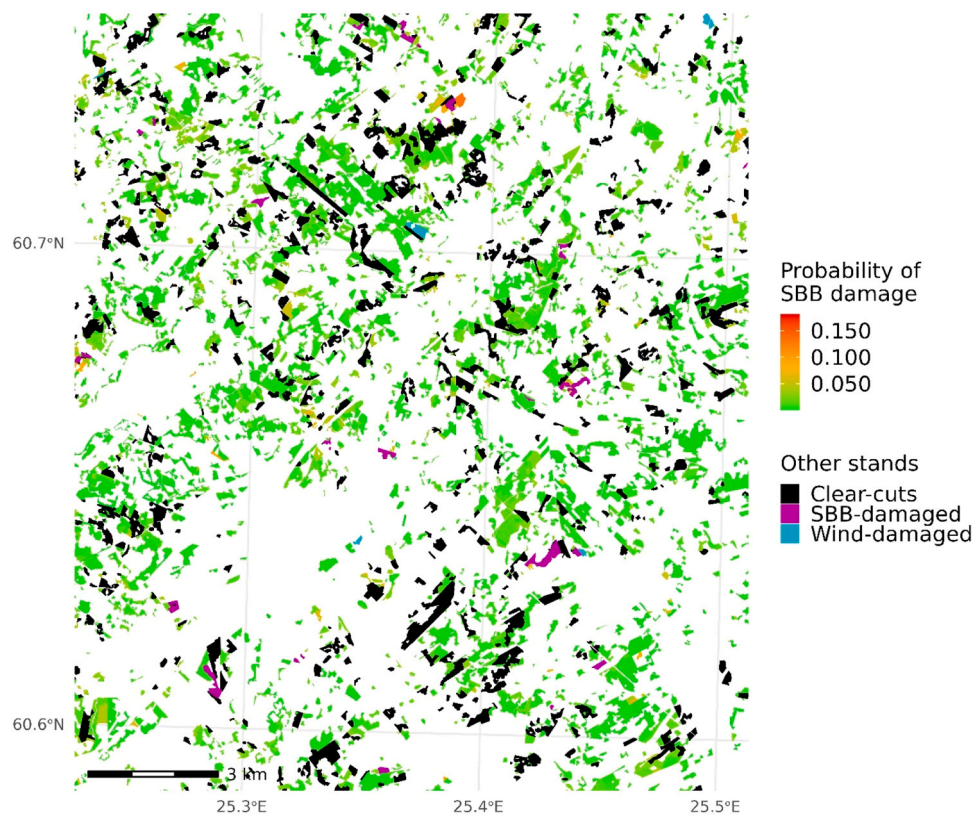


Fig. 7. Map of predicted probability of *Ips typographus* (SBB) damage in Norway spruce stands in 2022, in an example area from Uusimaa, as detailed area from Fig. 6, with probabilities estimated conditionally on region-level random effect. Most of the Norway spruce stands had low probability values. The clear-cut stands are from 2017 to 2022. The wind- and SBB-damaged stands are from 2020 and 2021.

Modelling the probability of *I. typographus* damage

The developed models predicted the probability of SBB damage in the 11.4 million ha of forestry land available for wood supply in Finland. Prior studies in other countries have covered areas up to 2.1 million ha (de Groot and Ogris, 2022), but prior Finnish studies have only covered up to 13,500 ha (Blomqvist et al., 2018). Our use of broad-scale infestation and non-infestation data with precise stand-level locations helps overcome the major limitation in risk modelling, namely the lack of location-specific information combined with the substantial computational demands associated with processing it (Fernández-Carrillo et al., 2024; Nardi et al., 2023; Seidl et al., 2011). Probability models help generate stand-level operational risk maps, providing a practical tool for proactive risk management. Although we used a broad set of known SBB attributes which can predispose Norway spruce to SBB damage, such as stand, landscape and climatic attributes, our work did not consider combined drivers (e.g. heat and drought) or SBB population fluctuations, which may impact the risk of SBB damage (Faccoli and Stergulic, 2004; Netherer et al., 2019; Seidl et al., 2011).

Considering the extensive geographical scope, 11.4 million ha with more than two million Norway spruce stands, heterogeneous drivers and inherent complexity of the system under study, our models accounted for a meaningful proportion of the observed variation. Unexplained variation likely reflects unmeasured local attributes such as microclimate, beetle populations, soil, prior tree health and unreported wind or beetle damage. It may be possible to generate a single model for the study area by extending the time series, adding predictors that account for local conditions or increasing spatial resolution using damage volumes or counts of SBB-damaged trees. These refinements would better capture variability in SBB damage, particularly near the beetle's northern range limit, where stronger environmental constraints lead to greater temporal variation in survival and reproduction (Brown et al., 1995; Sexton et al., 2009). The damage patterns caused by SBB under

boreal conditions in Finland contrast with those observed in Central Europe, where infestations tend to occur more frequently and under different climatic and forest management contexts (Seidl et al., 2011). Advanced statistical methods — such as geographically weighted regression, Bayesian spatial modelling, and many other modelling techniques — can contribute to building a more comprehensive model that captures full-area spatial patterns (Banerjee et al., 2014; Bivand et al., 2008; Seidl et al., 2011).

In comparison with estimated probabilities in Central Europe (de Groot and Ogris, 2019; Kovárník et al., 2025), the low estimated probabilities of SBB damage across the study area are likely due to the area's proximity to the beetle's northern range limit, where multiple constraints — particularly climatic conditions — limit SBB activity (Annala, 1969; Romashkin et al., 2020; Tikkanen and Lehtonen, 2023). However, the predicted probability of SBB damage was higher in the southern sub-area, consistent with previous studies reporting greater damage intensity (Eriksson et al., 2007; Pulgarín et al., 2024) and a higher concentration of damage hotspots (Pulgarín et al., 2025). The observed difference in probability of SBB damage between northern and southern sub-areas, and in comparison, to damage probabilities in Central European forest, could stem from contrasts in forest structure and climatic conditions, which are discussed in the next sections.

Effects of stand and landscape attributes

Distance to clear-cuts was the most influential landscape attribute on SBB damage likelihood. Proximity to clear cuts — whether resulting from routine forestry activities or earlier wind or SBB damage — has been linked to increased local beetle activity (Gohli et al., 2024; Müller et al., 2022; Pulgarín et al., 2024). Specially forest edges are particularly predisposed to colonisation by SBB (Kärvelo et al., 2014; Kautz et al., 2011). Our analysis indicates that distances to clear-cuts of approximately 500 m or less substantially increase the likelihood of SBB-damage, confirming Pulgarín et al. (2024). Although clear-cuts do

not consistently promote damage hotspots (Pulgarín et al., 2025), new edges of clear-cuts can create favourable microhabitats with the ideal conditions for beetle reproduction (Müller et al., 2022; Stříbrská et al., 2022). These conditions include weakened or wind-felled trees (Louis et al., 2015) and increased edge temperatures, especially increased bark temperatures (Stříbrská et al., 2022), and the incidence of direct solar radiation. This may induce stress in Norway spruce trees and facilitate SBB development, flight activity and increased dispersal distances (Hinze and John, 2019; Lindman et al., 2023; Wermelinger and Seifert, 1999). In particular, south-facing edges experience higher temperatures and higher attack probability (Lindman et al., 2023). These circumstances enhance the beetles' ability to synchronise attacks and exceed host defensive capacity, consistent with the epidemic phase of population dynamics (Hlásny et al., 2021; Wermelinger, 2004). We therefore suggest that the high susceptibility to SBB damage at new edges of clear-cuts should be considered in proactive risk and forest management. Considering the probability of SBB damage when planning spatial and temporal harvesting and decreasing the edge-length/cut-area ratio could improve risk management. Selective and timely removal of colonised trees and the use of selective cuttings in Norway spruce forests instead of clearcutting, when appropriate, may also help decrease the area of vulnerable edges.

The second most impactful attribute on the probability of SBB damage was stand mean diameter, which has been previously reported to increase the probability of SBB damage (Göthlin et al., 2000; Wermelinger, 2004). It is important to indicate that mean diameter and age are positively correlated, and diameter and height as well, although these relationships may be modified by other parameters such as site quality and stand density. Older trees with larger diameters tend to have thicker bark and more phloem than younger and smaller trees, providing ideal conditions for beetle attacks (Grunwald, 1986; Kärvelo et al., 2014; Wermelinger, 2004). Tree height like diameter is positively related to the likelihood of infestation by SBB (Müller et al., 2022). However, younger, smaller trees may still be attacked during epidemic population levels (Hlásny et al., 2021).

The volume of all other tree species than Norway spruce has a small but significant effect on the probability of SBB damage. The probability of SBB damage increases as the volume of non-spruce trees approaches zero inside a 500 m radius of the target stand. Such a decrease probably reflects a corresponding increase in Norway spruce volume, which is associated with higher damage likelihood in the southern sub-area, as well in other boreal forests (Müller et al., 2022). In an equivalent way, Norway spruce volume is positively related to higher SBB population, although the researchers evaluated a bigger buffer (5 km) around traps (Gohli et al., 2024), and to probability of SBB attack (Müller et al., 2022). Overall, tree diversity can reduce the likelihood of new beetle damage, what has been demonstrated in Northern Europe (Klapwijk and Björkman, 2018; Müller et al., 2022) and in Central Europe (Kovárník et al., 2025). Probably, it's not just diversity that reduces SBB probability, but lower host availability (de Groot et al., 2023), likely due to fragmented Norway spruce cover limiting access to new susceptible stands. Several reasons may explain the benefits of mixed stands, such as improved soil moisture retention, greater natural enemy activity, physical barriers to beetle movement and disrupted olfactory cues (Felton et al., 2016; Klapwijk et al., 2016; Kozhoridze et al., 2024; Zhang and Schlyter, 2004).

In our study, stands near recent SBB damage faced a higher probability of SBB damage, which is an expected pattern (Müller et al., 2022) and was found in an earlier study in the same study region (Pulgarín et al., 2024). This density-dependent effect has been identified as a key driver of new SBB damage (de Groot and Ogris, 2019; Faccoli and Stergulc, 2004). Notably, the probability of SBB damage peaks when damage occurred one year earlier, suggesting that while attacks fuel beetle populations in the next year, their influence declines over time (de Groot and Ogris, 2019; Müller et al., 2022). Proximity to previously infested stands also will contribute to the formation of local damage

hotspots and their recurrence (Pulgarín et al., 2025).

Finally, proximity to wind-damaged stands played a relatively minor role in our predictive models. This weak effect likely reflects the absence of major wind damage events during 2018–2020 in the study area. This weak effect is notable given its recognition as a key trigger of SBB damage (Eriksson et al., 2007; Økland et al., 2015). The lagged effect of wind damage is longer than that of previous SBB damage, likely because in cooler climates wind-thrown trees desiccate more slowly and thus remain suitable for colonisation over an extended period. In our southern sub-area, wind damage two years earlier (WD_{y-2}) had a greater effect than more recent events (WD_{y-1}), but WD_{y-1} had higher variability. Meanwhile, the observation that WD_{y-2} had contrasting effects in the two sub-areas should be addressed in future studies. In particular, the effect of proximity to WD_{y-2} for decreasing the probability should be interpreted with caution, as this is not supported by previous research.

The Forest Damage Prevention Act of Finland (Finlex, 2013) requires that damaged trees accounting for more than 10 m³ of weakened trees (e.g. wind- or beetle-damaged) be removed before adult beetles emerge. When this salvage logging leads to the creation of new forest edges, it may also increase the probability of SBB damage in the future. Beyond the direct effects of wind and SBB damage on subsequent infestation risk, removal actions may further promote new attacks by creating favourable conditions for SBB. This is especially likely in cases when salvage cuttings are done too late to control bark beetle populations (Weslien et al., 2024).

Effects of climatic attributes

Unexpectedly, given that both temperature and reduced precipitation have been widely reported as major drivers of beetle damage (Kovárník et al., 2025; Wermelinger, 2004), climatic attributes played a limited role in predicting the probability of SBB damage in this study. Climatic conditions, specifically low thermal conditions, have historically limited SBB development in our study area (Annala, 1969; Tikkanen and Lehtonen, 2023), also in locations where temperatures are higher than in our study area (Kovárník et al., 2025; Økland et al., 2015; Wermelinger, 2004). Our predictive models included climatic attributes representing both the current year and the previous year to capture lagged effects. Yet, most climatic attributes showed low statistical significance or small effects, while only a few displayed high significance and strong effects on the probability of SBB damage. This overall weak contribution does not mean that climate is unimportant, but rather that its effects may be non-linear or may arise through interactions not captured in our analysis such as voltinism type. This finding likely reflects unexpected responses of SBB populations to environmental attributes near the species' northern range limit, where conditions may be suboptimal for the species.

In this respect, literature suggest the presence of two SBB phenotypes in our study area (Schebeck et al., 2021; Schroeder and Dalin, 2017). The first one is in the northern sub-area, where a significant part of the individuals may show obligate diapause independent of photoperiod and be univoltine (Schebeck et al., 2021; Schroeder and Dalin, 2017). The second one is in the southern sub-area, where individuals exhibit predominantly facultative, photoperiod-regulated diapause (Schroeder and Dalin, 2017). Because diapause is linked to temperature and photoperiod (Doležal and Sehna, 2007), their interaction likely shapes voltinism in the south, as earlier observations suggest potential for second generation in warm summers in Southern Finland (Pouttu and Annala, 2011). However, experimental evidence disentangling these factors is still lacking for northern latitudes and would be very valuable for determining the potential number of generations under future climate conditions.

Of the climatic attributes affecting the probability of SBB damage, precipitation had a limited impact, though it had both lagged and immediate effects. Earlier studies link reduced precipitation to beetle damage (Gohli et al., 2024; Grodzki et al., 2006; Kozhoridze et al., 2024) mainly driven by drought-induced weakening of Norway spruce (Netherer et al., 2024, 2015; Økland et al., 2015). Notably, trees adapted

to chronically dry sites tend to experience fewer beetle attacks (Christiansen and Bakke, 1988; Netherer et al., 2019), but once SBB populations reach epidemic levels, even well-defended and/or trees having low diameters succumb (Hlásny et al., 2021). Low precipitation coupled with high temperatures often leads to a high incidence of attacks, which should be explored in future studies, especially when linked to soil wetness, as dryness predispose the Norway spruce to SBB attack (Müller et al., 2022) and low soil moisture correlated negatively with SBB population levels (Gohli et al., 2024).

The maximum number of consecutive hot days had a stronger impact on SBB damage probability than any other climatic attribute. It increased the likelihood in the northern sub-area but reduced it in the southern sub-area. Previous studies have shown that temperatures above 25°C fall in the beetle's optimal range for development, flight activity and dispersal, leading to synchronised mass attacks — a key mechanism to overcome tree defences (Funke and Petershagen, 1994; Grodzki et al., 2006; Hinze and John, 2019; Wermelinger and Seifert, 1999). However, our results in the southern sub-area show the opposite pattern. A similar observation from Slovenia showed that increased temperatures in the previous growing season decreased fir bark beetle outbreaks in the current year (de Groot and Ogris, 2019). This was possibly because prolonged heat waves with temperatures above the optimum for development disrupt the beetle's growing cycle and its capacity to infest new hosts (Økland et al., 2015; Wermelinger, 2004; Wermelinger and Seifert, 1999). In Finland, however, current temperatures may not yet meet those critical extremes where beetle activities are disrupted (Hinze and John, 2019; Økland et al., 2015; Wermelinger and Seifert, 1999). In contrast, temperature in a 3-year time lag, correlated positively with SBB higher population levels in Norway (Gohli et al., 2024), which in turn have been positively correlated with higher SBB damage (Faccoli and Stergulc, 2004). Thermal sum has in previous studies determined the probability of a Norway spruce tree dying because of SBB attack (Kovárník et al., 2025).

The contrasting effects of heatwaves between the northern and southern sub-areas in our study, and the relationship of SBB population levels to temperature in higher time lags than what we evaluated, highlight the complexity of thermal responses. It is important to use longer time series in future studies to investigate how beetle populations adapt to regionally varying temperature conditions in northern countries, particularly with regard to voltinism types. Thermal sum did not have a significant effect in our predictive models, though this does not imply that its effect on the likelihood of SBB damage is negligible. The lack of statistical significance could have several causes: i) random intercepts may absorb variation associated with thermal sum; ii) its relationship with the probability of SBB damage may be non-linear; iii) its individual effect may weaken when other predictors are included; iv) or the division of the study area into two sub-areas. Alternatively, its influence might emerge only through interactions with other predictors or combined with lag effects not included in the current models. Higher thermal sums may increase flight activity, for instance, but this effect could diminish — or even reverse — when precipitation is also high. From the host's perspective, when available water in the soil is low, high temperatures increase the vapour pressure deficit and enhance transpiration, weakening tree defences (Chia and Lim, 2022; Hartmann et al., 2022). However, this vulnerability is often reversed by precipitation (Harrington et al., 2001; Hartmann et al., 2022; Potterf et al., 2025). Studying these interactions may help explain the vulnerability of Finnish forests to SBB attacks.

Forest risk management

Several forest management strategies may help mitigate SBB damage risk. Given the high probability of infestation in landscapes dominated by mature Norway spruce stands with limited presence of other tree species, diversifying forests represents a key opportunity. Specifically, we recommend reducing the proportion of mature Norway spruce stands and enhancing diversity in both age classes and species composition — particularly in southern Finland, where mature Norway spruce stands

are prevalent and predisposed to SBB damage (Korhonen et al., 2021; Pulgarín et al., 2024). Selective cuttings of infected trees may also help reduce the length of forest edges vulnerable to SBB damage in appropriate sites (Komonen et al., 2020). However, selective cuttings may increase the probability of harvesting damage (Hantula et al., 2025; Nevalainen, 2017) and reduce forest productivity, which affects long-term wood supply (Brunner et al., 2025).

Wind- and SBB-damaged stands require new interventions. This sets off a self-reinforcing sequence — wind or SBB damage → leads to the removal of affected trees and edge creation → which results in new SBB-damaged stands, restarting the cycle — revealing the importance of reconsidering how damaged stands are managed (Potterf et al., 2025). Timely salvage logging is widely recommended to limit further damage (Hlásny et al., 2021; Kuhn et al., 2022; Wermelinger, 2004), but its effectiveness hinges on the near-total removal of affected trees, typically requiring > 95 % logging intensity (Dobor et al., 2019; Lindman et al., 2023). It often leads to clear-cuts, which may induce new SBB damage (Stříbrská et al., 2022). One early intervention alternative, which has been proposed for controlling other forest insect pests (Ciesla, 2011), is removing individual infected trees from the forest, leaving smaller gaps and avoiding the creation of cutting edges (Ciesla, 2011). This practice may promote structural and compositional diversity and increase long-term resistance to SBB (Klapwijk and Björkman, 2018; Nevalainen, 2017). However, the effectiveness of selective cutting in managing SBB damage has not yet been documented in Finland.

Another way to address future SBB damage is through enhanced monitoring with annually updated stand-level risk maps of SBB damage, such as those developed in this study (Fig. 6 & Fig. 7). Integrating such maps into forest policy and operational planning would allow forest managers to prioritise intervention in high-risk stands and regions. This targeted approach could improve the efficiency of surveys for SBB detection, whether conducted by humans (Kautz et al., 2023), scent detection dogs (Vošvrđová et al., 2023), or, on a larger scale, aerial remote sensing (Turkulainen et al., 2025). Accurate, frequently updated risk maps would help allocate resources more effectively, reducing costs and increasing the success of SBB control measures.

5. Conclusions

Our results show that the probability of SBB damage in Finland is affected by stand, landscape and climatic attributes. Mature Norway spruce stands offer an ideal habitat for the beetle. Because proximity to clear-cuts is the strongest predictor of SBB damage, there is an urgent need to reconsider how logging operations are conducted, especially salvage logging of SBB-damaged stands. Given that the current practice of SBB salvage logging increases the likelihood of SBB damage, alternative proactive risk management actions should be considered at different spatial and temporal scales. In the short term, SBB damage probability maps, like those presented in this study, can help forest owners and managers identify high-risk stands and support cost-effective monitoring and timely intervention. Further research is needed to determine which combinations of management strategies (e.g. forest structural diversification and alternative harvesting methods) are most effective under future changing climate conditions. We suggest integrating predictive models of SBB damage probability into forest management simulators to assess how controlling key damage drivers affects ecosystem services, including timber yield, carbon storage and recreational value. Our findings provide a foundation for evidence-based, proactive risk management in Finnish forests.

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CRedit authorship contribution statement

Juha Aalto: Writing – review & editing, Data curation. **Suraj Polade:** Data curation. **Olli-Pekka Tikkanen:** Writing – review & editing, Validation, Project administration. **Heli Peltola:** Writing – review & editing, Project administration, Funding acquisition. **John Alexander Pulgarín Díaz:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Lauri Mehtätalo:** Validation, Formal analysis. **Markus Melin:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.foreco.2025.123436](https://doi.org/10.1016/j.foreco.2025.123436).

Data availability

Data used in this study are available on the Metsäkeskus website (<https://www.metsakeskus.fi/en>).

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