Forest Ecology and Management 563 (2024) 121964

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Impact of management strategies on forest susceptibility to spruce bark beetle damage and potential trade-offs with timber production and biodiversity

Teresa López-Andújar Fustel [a,*], Karin Öhman [a], Maartje Klapwijk [b], Michelle Nordkvist [b], Lars Sängstuvall [c], Tomas Lämås [a], Jeannette Eggers [a]

[a] Department of Forest Resource Management, Swedish University of Agricultural Science, Umeå SE-90183, Sweden
[b] Department of Ecology, Swedish University of Agricultural Sciences (SLU), Box 7044, Uppsala SE-75007, Sweden
[c] Bergvik Skog Öst, Sveavägen 9, Stockholm 111 57, Sweden

ARTICLE INFO

Keywords:
Spruce bark beetle
Forest management
Optimization
Trade-off
Forest susceptibility
Management strategies

ABSTRACT

The European spruce bark beetle (SBB) is an important insect pest in many countries such as Sweden and has caused the loss of millions of trees over the past few decades. Forest management targeting key variables in the forest can be a potential tool to decrease SBB susceptibility. In this paper, we simulated forest development over a 70-year planning horizon and evaluated the effect of different forest management strategies on spruce bark beetle susceptibility, timber production and biodiversity indicators. We used national forest inventory plots located in Kronoberg county, Southern Sweden, from 2016 to 2020 to perform the analyses. A reference strategy mimicking current management practices was simulated and compared with four other management strategies that can be an alternative to decrease spruce bark beetle damage. The four management strategies were (1) mixed forest stands, (2) shorter rotations and no thinnings, (3) prolonged rotations and (4) continuous cover forestry. The strategies differed in how and when regeneration, pre-commercial thinning, thinnings and final fellings were performed. The optimization of each of the strategies was aimed at reducing spruce bark beetle susceptibility while simultaneously investigating trade-offs with a range of timber production demands. In addition, we simulated a combined strategy where any of the strategies could be chosen with the objective of reducing spruce bark beetle susceptibility. Also, we evaluated each strategy with respect to biodiversity indicators described in the Swedish environmental quality objective Living Forests. The results show that a combination of all strategies is the most effective option to manage the forest to achieve the lowest average susceptibility in the analysed forest area. Shorter rotation management also resulted in low susceptibility. In addition, management strategies leading to large reductions in the abundance of large stem diameter Norway spruce trees in the landscape achieve lower susceptibility values. Our results suggest that various management strategies, alone or in combination with others, can be successfully employed to decrease forest susceptibility to spruce bark beetle damage. However, achieving multiple management objectives simultaneously, such as timber production and promotion of biodiversity, may require additional constraints in the mathematical models in addition to the settings used to describe each of the strategies. Future work should explore incorporating these additional constraints to better optimize management decisions.

1. Introduction

Forest damages have increased for several decades in Europe (Schelhaas, 2008; Seidl et al. 2014). This increase is partly due to climate change, and partly due to changes in forest structure and composition, which play an important role in making a forest prone to damage (Seidl et al. 2011). Seidl et al. (2011) emphasized the strong influence that forest management can have on changing forest conditions to decrease susceptibility to disturbances. According to their findings, forest management and climate change contribute to a similar extent to disturbance damage. Trends of increasing forest damage over the last decades have led to a rising interest in forest management

* Corresponding author.
E-mail address: teresa.fustel@slu.se (T. López-Andújar Fustel).

https://doi.org/10.1016/j.foreco.2024.121964
Received 5 December 2023; Received in revised form 26 April 2024; Accepted 29 April 2024
Available online 20 May 2024

strategies to reduce forest susceptibility to disturbances (Seidl et al. 2014).

One of the major insect pests causing forest damage in Central Europe and Sweden is the European spruce bark beetle or eight toothed spruce bark beetle (*Ips typographus;* Coleoptera: Curculionidae, Scolytinae), a Norway spruce specialist (*Picea abies* (L.) H. Karst.). The European spruce bark beetle (SBB) is known for its eruptive outbreaks after large storm fellings or prolonged periods of drought (Christiansen & Bakke, 1988; GrÉGoire & Evans, 2004; Wermelinger, 2004). During endemic phases, SBB damage frequently occurs only on dying (wind felled) or weakened trees. However, during the outbreak phase, high SBB population densities allow large-scale attacks to overcome tree defences of healthy trees as well (Schroeder & Lindelöw, 2002; Komonen et al. 2011). In Sweden, losses attributed to SBB averaged less than 1 million m^3 of timber per year until the year 2000. Although disturbance damage assessments during that time were not as precise as they are today, the two decades following the year 2000 have experienced notably larger losses in comparison. The annual average of damaged timber over the last decade has approached 3 million m^3. However, when considering the years 2018–2021, this figure increases to 7 million m^3 (Skogsstyrelsen, 2021; Skogsstyrelsen, 2022). In 2018 a prolonged warm and dry period resulted in a SBB outbreak that is still ongoing.

Forest management in Sweden over the last century has resulted in high amounts of even-aged, mono-specific stands (Skogsdata, 2023). Such stands might be more susceptible to abiotic disturbances like storm and drought, and also to insect pests such as SBB due to a large availability of host trees and appropriate breeding material (Jactel et al. 2017). SBB damage on Norway spruce trees occurs mostly in Southern Sweden (the regions of Götaland and Svealand), where approximately 65% of the forest area is dominated by this tree species (Skogsdata, 2023). SBB damage risk is positively correlated with Norway spruce stem diameter (Kärvemo et al. 2016), and Norway spruce volumes across the landscape. Moreover, older trees are also associated with a high infestation risk and tree mortality compared to younger trees (e.g. Netherer & Nopp-Mayr, 2005; Overbeck & Schmidt, 2012; Kärvemo et al. 2016). Norway spruce trees with a diameter under 20 cm lack a bark thickness suitable to successful SBB reproduction (Lekander 1972). Around two thirds of Norway spruce standing volume in Sweden has a diameter above 20 cm, constituting potential breeding material for SBB (Skogsdata, 2023). However, the severity of SBB outbreaks is correlated with the annual number of completed SBB generations per year, which is directly linked with climate conditions such as temperature variations or drought (Dutilleul et al. 2000; Berg et al. 2006; Seidl et al. 2007). In Southern Sweden, SBB could reach two generations in today's climate when weather conditions are favourable, while in Northern Sweden the temperature condition will not favour more than one generation per year (Jönsson et al. 2009, 2011; Jönsson & Bärring, 2011). Therefore, the projections of global warming combined with the anticipated higher frequency of extreme drought periods are expected to lead to increased SBB damage. In years with extreme drought, SBB will be able to benefit from warm summers and reduced tree vitality caused by lower water supplies (Netherer & Hammerbacher, 2022).

In this context, it is important to investigate how forest management can influence the susceptibility to SBB damage. Management strategies such as shorter rotation periods or the promotion of mixed tree-species stands have been studied in connection to insect damage risk (e.g. Overbeck & Schmidt, 2012; Klapwijk et al. 2016). Overbeck & Schmidt (2012) suggested that shortening rotation periods, promoting greater proportions of diverse tree species, and restricting the planting of Norway spruce to moist and shadowed slopes could be beneficial to reduce the risk of infestation. Also, lowering the proportion of large trees in the landscape through continuous cover forestry (CCF) management could potentially reduce susceptibility (Björkman et al. 2015), but empirical evidence is sparse. Shorter rotation periods can limit the window of opportunity for SBB colonization by reducing the prevalence of large Norway spruce trees in the landscape over time (Jönsson et al. 2015; Zimová et al. 2020). However, shorter rotations can reduce the amount of old Norway spruce forest and lead to habitat fragmentation for SBB predator species dependant on old-growth forests (Andersson et al. 2022). On the other hand, prior research on the promotion of broadleaf species in the forest and the reduction of pure Norway spruce stands presents contrasting arguments regarding how SBB susceptibility is influenced (Faccoli & Bernardinelli, 2014; de Groot et al. 2018, 2023; Müller et al. 2022).

The overall objective of this study is to evaluate how forest management strategies affect the forest's susceptibility to damage from SBB over time. More specifically, we aim to 1) assess the impacts of adaptive management strategies on SBB susceptibility, 2) evaluate how these management strategies influence timber production and biodiversity indicators, and 3) provide forest managers with knowledge on how they can modify SBB susceptibility through forest management strategies. Forest susceptibility to SBB damage and the different management strategies were simulated using an advanced forest decision support system for a case study area in southern Sweden, using a simulation-optimization approach. The simulations were done over a planning horizon of 70 years under one management strategy attempting to resemble practical forestry in Sweden and four adaptive forest management strategies. In the optimization, forest susceptibility to SBB was minimized under ten different harvest volume demand scenarios.

2. Materials and methods

2.1. Study area

The study area is Kronoberg County in southern Sweden, consisting of 689 000 ha of forest (Skogsdata, 2023) (Fig. 1). We chose this area as case study, as it represents the forest type in Sweden that is most affected by SBB. The county's productive forest is dominated by conifers, which cover more than 75% of the forest area. Norway spruce dominates more than 56% of the forest area in the county, equivalent to 368 041 ha. Forest dominated by Norway spruce has a mean age of 36 years and a site index of over 28 m (H100) in 90% of the area. At present, 82% of Kronoberg's Norway spruce forests are younger than 75 years (Fig. 1). The current age class distribution is largely a result of the 2005 storm named Gudrun (southernmost part of Sweden), where more than 70 million m^3 of timber were damaged and large forest areas that were blown down had to be regenerated. In the analyses, 680 National Forest Inventory (NFI) plots from years 2016–2020 (plot radius 7 m (temporary plots) and 10 m (permanent plots)) were used to represent the 368 041 ha of Norway spruce dominated forest in Kronoberg county (Fridman et al. 2014). Forest areas dominated by other species or classified as nature reserves in the NFI plots were excluded from the analyses.

2.2. Forest management strategies

Different forest management strategies were simulated using the PlanWise software within the Heureka forest decision support system (Lämås et al. 2023). Heureka PlanWise enables informed decisions about how to manage the forest according to designated management settings and management goals. PlanWise simulates forest growth development and uses mathematical models and algorithms to solve user-defined optimization problems. It runs in two main steps: 1) a set of potential treatment schedules is generated for every plot (or stand) based on the user-defined settings of different management strategies. Here, the treatment schedules are simulated in steps of five years (equivalent to one period) and over the planning horizon stipulated by the user. For each plot, up to twelve treatment schedules per management strategy are generated over time. Treatment schedules refer to the sequence and timing of silvicultural practices that take place in a plot (or stand) during the planning horizon. 2) The optimal combination of treatment schedules for each plot (or stand) is decided by solving an optimization problem consisting of an objective and constraints defined by the user.

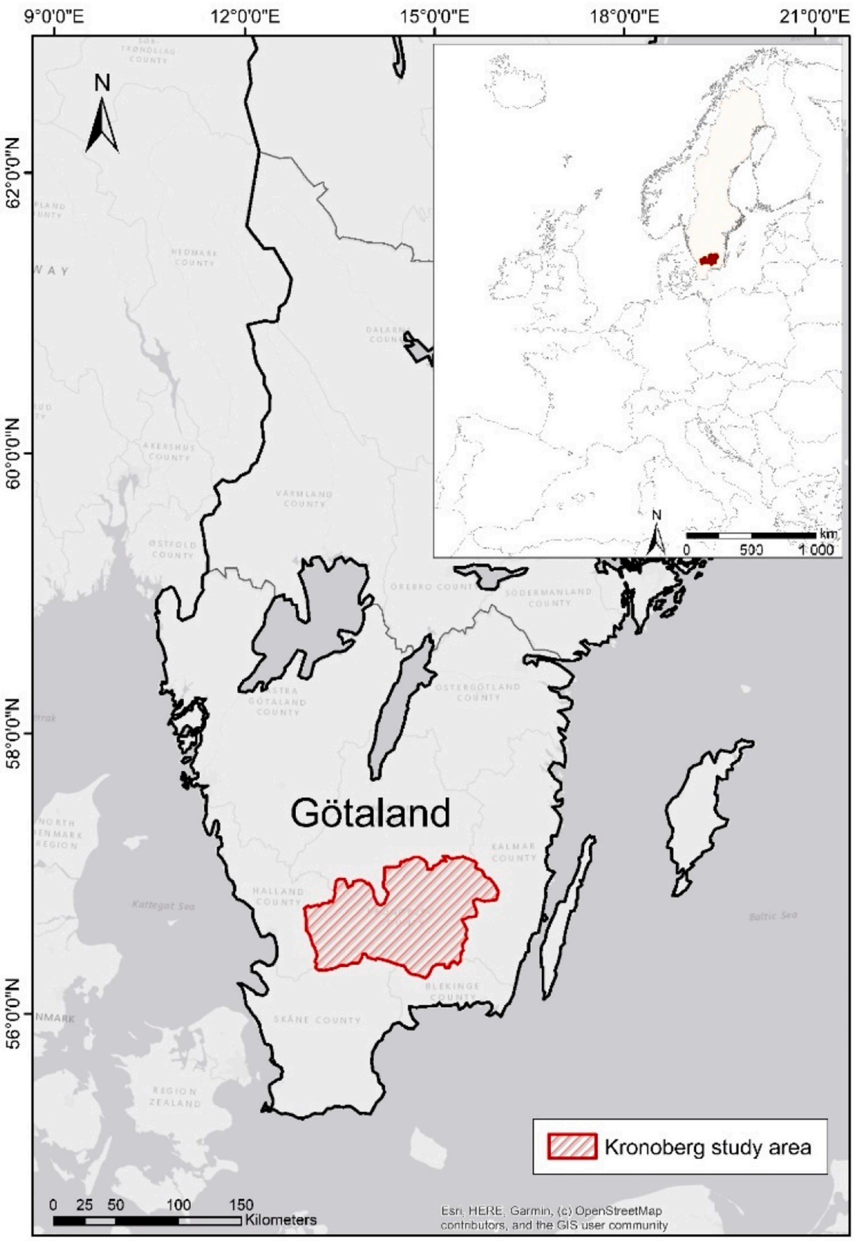


Fig. 1. Map of Kronoberg study area situated in Götaland region, Southern Sweden. The large grey areas within the country represent lakes.

In this study, up to 12 treatment schedules per management strategy were simulated individually for the forest area (Table 1). 1) The *Reference strategy* (REF) reflects current management practices in Sweden; 2) The *Mixed forest strategy* (MIX) aimed to increase tree species diversity, increase the density of birch trees in the forest over the planning horizon and reduce the density of suitable host trees for SBB, i.e. diminish the density of Norway spruce trees. Typically, birch regeneration is quite high at early stages of the rotation period and then decreases over time (Fahlvik et al. 2005). For this reason, active management in MIX was performed to maintain the density of birch trees over the whole rotation; 3) In the *Short rotation without thinnings* (SHORT) strategy, rotation length was reduced to decrease the abundance of large diameter trees of Norway spruce in the forest. This measure also shortens the period of time in which Norway spruce forests are susceptible to SBB attack. 4) In the *Long rotation* (LONG) strategy, rotation times were elongated to favour biodiversity. 5) In the *Continuous cover forestry* (CCF) strategy, a series of selective fellings (implemented as thinnings from above) aim to reduce the density of trees with large diameters. CCF management typically also increases local (stand level) tree size diversity and favours a wider range of forest structures compared to even-aged management. The creation of different forest structures and species composition can foster the diversity of organisms that could potentially be natural enemies of SBB (Klapwijk et al. 2016). In addition to the previous management strategies, an additional combined strategy (ALL) was also simulated for each NFI plot within the study area. For the combined strategy ALL, management schedules from all five strategies could be selected and applied in the forest area (see the optimization section).

2.2.1. SBB susceptibility index

We used a susceptibility index developed by Nordkvist et al. (2023) to quantify forest susceptibility to SBB attack for each potential treatment schedule (Appendix E). The value of the index gives a relative measure of susceptibility, i.e., it is not a measure of the probability of getting damage but a measure that compares the susceptibility of different forest stands in relation to one another. The index was originally intended for stand-level application to compare different

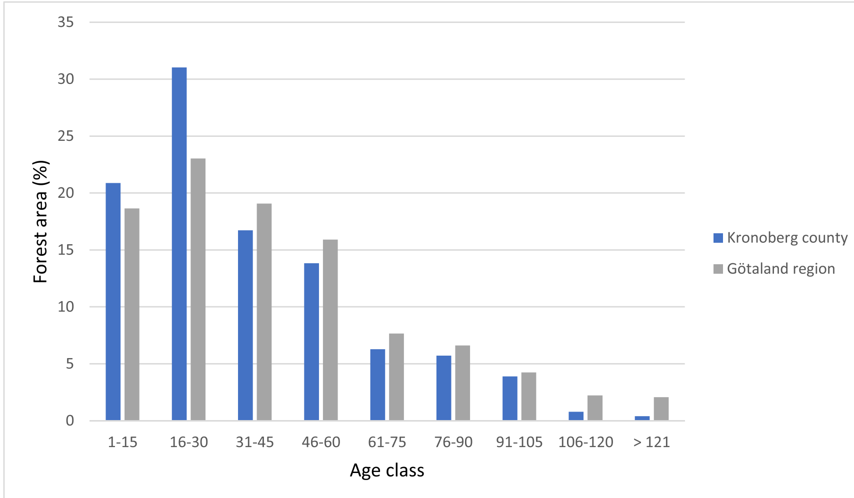


Fig. 2. Initial age class distribution for Norway spruce dominated forest (368 041 ha) in Kronoberg county, Götaland region (see Fig. 1).

management strategies; however, in this study, we computed the mean index value over each simulated 5-year period for every NFI plot in Kronoberg county. The index considers plot characteristics (Norway spruce volume and mean stem diameter, birch volume, stem density, age structure), soil moisture and temperature sum that are important for spruce bark beetle attack. The index ranges from 0 to 3.66 where higher values mean higher susceptibility. There are three initial criteria to be fulfilled for the index to take a value other than 0; temperature sum $>$ 745 °C, volume of Norway spruce > 0, and plot mean stem diameter (Norway spruce) $\geq$ 20 cm. The contribution of the individual parameters to the total value of the index is determined by their importance on increasing forest susceptibility to SBB attack. For example, Norway spruce volume and temperature sum are considered highly important based on scientific evidence (Jönsson et al. 2009; Romashkin et al. 2020; Fritscher & Schroeder, 2022), thus, each of their contribution weights equal to 1. Age structure, which is an important parameter for the CCF strategy, has a weighed contribution of 0.5 as the scientific evidence is ambiguous. The contribution of birch volume, important for the MIX strategy, is set to 0.2 as the scientific evidence based on field observations is ambiguous and sometimes contradictive. Heureka projects the development of stand susceptibility over time. Until a stand containing spruce has passed a stem diameter of 20 cm on average the returned susceptibility value is zero. In this work, we assumed that between harvesting and passing the tree diameter size threshold the stand is in a 'susceptibility free period' and in that way contributes to the average landscape-level susceptibility. In our work, when we present average susceptibility index values for a model landscape, these zeros are included in the susceptibility.

2.2.1.1. Optimization. To determine the best treatment schedule for each plot, two different optimization models were formulated and solved for each of the forest management strategies. The first optimization model aimed to maximize harvest volume production, whereas the second one minimized the SBB susceptibility index subject to harvest volume demands above certain thresholds detailed below. In the optimization models, potential treatment schedules were chosen among those that were available within the specific management strategy (REF, MIX, SHORT, LONG and CCF). In addition, in the ALL strategy, the optimization models could choose treatment schedules out of all the five individual management strategies. That is, in the ALL-case different strategies could be applied to different plots. For a complete mathematical description, see Appendix A and B.

First, we identified benchmarks for the maximum possible harvest that could be achieved by each of the five individual strategies and the ALL strategy without consideration to SBB susceptibility index. This was obtained by solving six optimization models where the aim was to maximize harvest volume subject to an even-flow constraint (Appendix A). The results (benchmarks) of this optimization where later used to demand a percentage of the maximum possible harvest volume when minimizing the SBB susceptibility index (Appendix B). Note that the benchmarks obtained from this optimization are different for each strategy, as the applied management during the planning horizon varies among them.

Second, we ran 54 optimization problems, nine for each individual strategy and nine for the ALL strategy. The optimization models here minimized the SBB susceptibility index over time (Nordkvist et al. 2023) subject to a gradually decreasing timber harvest demand compared to the benchmarks, i.e. harvest demands were lowered progressively, starting from 99% down to 75% (99, 98, 97, 96, 95, 90, 85, 80 and 75%), where no further decrease of harvest demand resulted in changes on the results. In all optimization problems, a constraint securing an even-flow of timber harvest over the planning horizon was applied. For the REF, MIX, SHORT, LONG and ALL strategies, an even-flow harvest constraint allowing up to 20% of harvest fluctuation between five-year planning periods was set (Appendix A). We had to adjust the harvest fluctuation of the CCF strategy to 21% to find feasible solutions of the optimization problem.

2.3. Post-optimization evaluation: indicators for timber production and biodiversity

To investigate and compare the performance of the results from each optimization regarding timber production, we looked at the total harvested volume over the planning horizon. For biodiversity, we used indicators that are applied to monitor the progress towards reaching the Swedish environmental quality objective Living Forests (https://sverigesmiljomal.se/miljomalen/levande-skogar/; last accessed 1 march 2023). The following three indicators were included in the evaluation:

- Old forest. Area of productive forest older than 120 years (the age stated for southern Sweden).
- Mature broadleaf-rich forest. Productive forest land older than 60 years where at least 25% of basal area corresponds to broadleaved tree species, for example, birch, aspen, oak, and beech.
- Forest with many large trees. Area of productive forest land with over 60 trees per hectare (minimum stem diameter for conifers: 45 cm, and for broadleaves 35 cm).

Table 1
The five forest management strategies simulated in Heureka PlanWise. In the sixth strategy (ALL), all of the five strategies below could be applied. For further information, see Appendix D.

Management strategy	Aim	Heureka settings
Reference (REF)	Resemble current practical forestry in Sweden.	• soil preparation and planting of Norway spruce seedlings after final felling, • precommercial thinning when trees are between 2 and 6 m high to remove tree species other than Norway spruce, • thinnings, up to two or three times during the rotation period, and avoided when trees +20 m high, • retention of 10 trees*ha^{-1} and 3 high stumps*ha^{-1} after final felling, • set aside 10% of forest area at final felling, and • as exception, after final felling in dry soil types, Scots pine (*Pinus sylvestris* L.) seedlings were planted instead of Norway spruce.
Mixed forest strategy (MIX)	Increase tree species diversity, such as the density of birch trees in the forest and, reduce the density of Norway spruce trees.	Same as REF but: • at regeneration, only 1200 seedlings per hectare were planted independently of site index (SI), and • after pre-commercial and commercial thinnings, 40% of stems should be birch and other non-Norway spruce species, if possible.
Short rotation without thinnings (SHORT)	Decrease the abundance of suitable host trees for SBB i.e., large stem diameter of Norway spruce.	Same as REF but: • no thinnings were allowed, • minimum final felling age was lowered by 10% and, • a maximum delay on the execution of the final felling was set to 15 years.
Long rotation (LONG)	Favour biodiversity promoting the aging of trees in the landscape.	Same as REF but: • minimum final felling age increased by 20%, and • a maximum delay on the execution of the final felling was set to 50 years.
Continuous cover forestry (CCF)	Increase local tree size diversity and favour a wide range of forest structures.	In this strategy, final fellings were not performed and the removal of timber from the forest was carried out by a series of selection fellings, implemented as thinnings from above.

3. Results

3.1. Trade-offs between harvested timber volumes and SBB index

The Pareto curves, which illustrate the trade-off between harvest volume and average susceptibility to spruce bark beetle colonization, showed a decline in the average SBB index (on average over the planning horizon) when harvest demands were reduced compared to the benchmarks (Fig. 3). The lowest average SBB index (0.6) was found for the ALL strategy. For most strategies - REF, MIX, SHORT, LONG and ALL - the lowest average SBB values were achieved already when harvest demands were decreased to around 90% of the maximum potential harvest (the curves are nearly horizontal below 90%). This point is different for every management strategy, and beyond it, further reductions of harvest volume demand to attain lower SBB index values, do not make a difference. For instance, for REF, once the harvest volume demand is decreased below 93% of the maximum achievable, a combination of treatment schedules that achieves further reduction in the SBB index value at the expense of harvest volume could not be found. However, CCF achieved its lowest value (1.7) already when harvest demands were set to 98% and harvested volumes did not show large changes below this value (Fig. 3). The combined strategy, ALL, obtained larger harvested volumes and lower susceptibility index values in comparison with the other management strategies alone. Compared to ALL, continuous cover forestry, CCF, produced on average 31% less harvested volume and approximately two times higher values of SBB susceptibility.

In further analyses, we selected two harvest demands, 100 and 90%, signalled as (+) and (*) respectively in Fig. 3, to show the impact of reducing SBB susceptibility. Additionally, we also displayed the results of a harvest demand of 75% in some figures to show an opposite to 100%.

3.2. Development of SBB susceptibility index and annual harvested volumes over the planning horizon

Forest development over the planning horizon showed differences among the strategies, and this was reflected on the average values of the SBB susceptibility index (Fig. 4). When maximizing harvest demand (HD) (timber volume) over the planning horizon, HD 100, (i.e., no consideration was made to reduce SBB susceptibility), SHORT had the lowest mean SBB index values, whereas CCF had the highest. REF and ALL had similar values throughout the planning horizon. LONG and MIX showed higher SBB index values than REF and ALL, with only CCF exceeding them. When minimizing the SBB susceptibility index while lowering the harvest demand to 90%, average SBB index values were slightly lower for all strategies except CCF (Fig. 4B). SHORT continued to be the strategy with the lowest average SBB values and, in contrast to HD 100, the ALL strategy also produced similar values to SHORT. Rotation times in the SHORT and LONG strategies are relative to REF. Accordingly, SBB index values in the REF strategy are in between SHORT and LONG.

The average annual harvested timber volumes during the planning horizon remained between 4 and 8 $m^3ha^{-1}year^{-1}$ (Fig. 5) for the highest harvest demand, 100%. For harvest demands 100 and 90%, REF and the combined strategy ALL produced the highest average harvested volumes, while the CCF strategy resulted in the lowest harvest levels. The annual harvested volume for LONG and CCF remained relatively stable regardless of harvest demands (Fig. 5).

3.3. Combined strategy (ALL)

When applying the ALL strategy, i.e., allowing the optimization model to pick treatment schedules from all strategies, the proportion of each management strategy varied among different harvest demands (Fig. 6). The highest harvest demand (100%), that did not consider minimizing the average SBB index, resulted in applying REF on more than 65% of the forest area, MIX on 17% and SHORT on 10%. LONG and CCF were employed the least when aiming to maximize harvest volumes. However, when lowering harvest demands to 90–75% of the maximum possible harvest volume, the prevailing strategy shifted to SHORT, being applied across 51–64% of the forest area respectively. The utilization of REF and LONG strategies diminished as harvest demands decreased, eventually being implemented on only 6% and 1% of the forest area for HD 75, respectively. In contrast, the MIX strategy exhibited a gradual increase, reaching up to 25% of the forest area for HD 75. The implementation of CCF strategy remained uniform, fluctuating within the range of 1–4%.

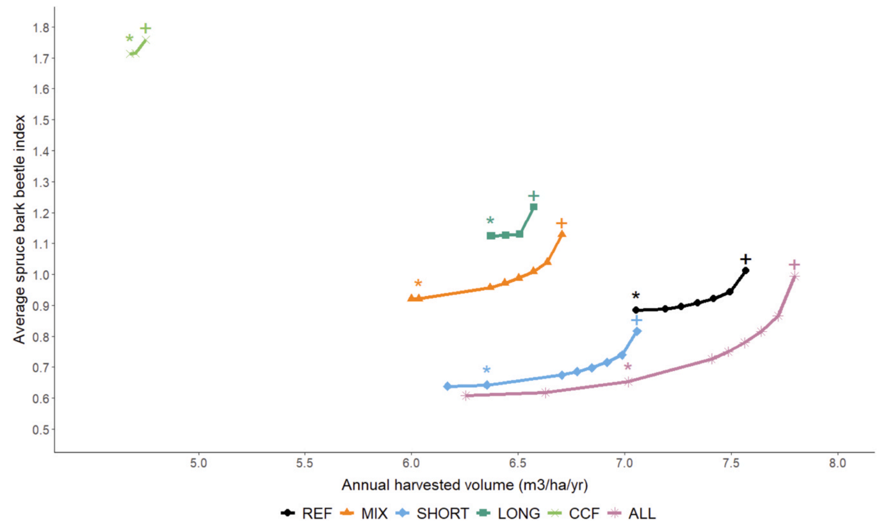


Fig. 3. Trade-off curves between harvested volumes within the 70-year planning horizon and average value of the SBB susceptibility index over the planning horizon. Each line represents an individual management strategy except for the violet line, which represents the combined strategy ALL, where treatment schedules from all strategies could be applied (see Table 1). The rightmost point (+) on each strategy indicates maximum harvest demand subject to an even-flow harvest constraint, and was estimated individually for each strategy, see Appendix A. In addition, harvest demand 90% is indicated by (*) in the figure. Each of the remaining points on the lines represent optimizations with the objective of minimizing the SBB index subject to a certain harvest demand (starting from right to left 99, 98, 97, 96, 95, 90, 85, 80 and 75%), and an even-flow harvest constraint over the planning horizon. For some strategies, such as LONG and CCF, harvest demands below 97 and 98%, respectively, did not produce different index values, and the points are superimposed. Note that x- and y-axis do not start in zero.

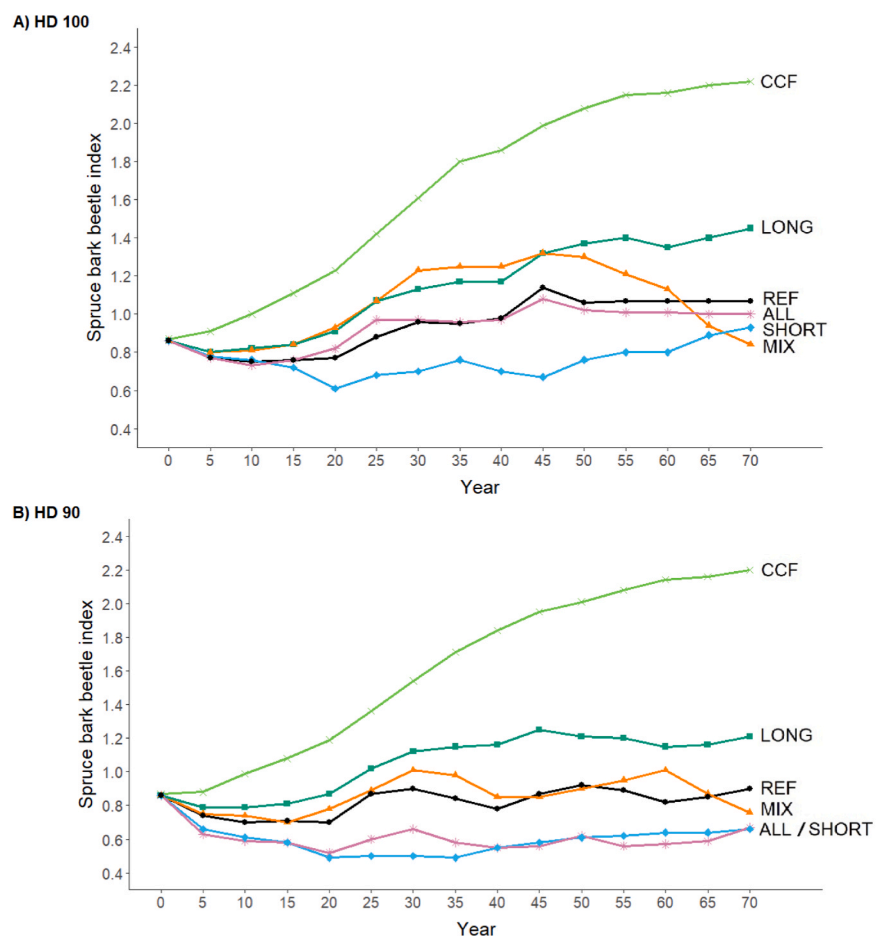


Fig. 4. Development of average value for SBB index during the planning horizon of 70 years and for every strategy. The development of the index is shown for harvest demands (HD) 100 (upper panel) and 90% (lower panel).

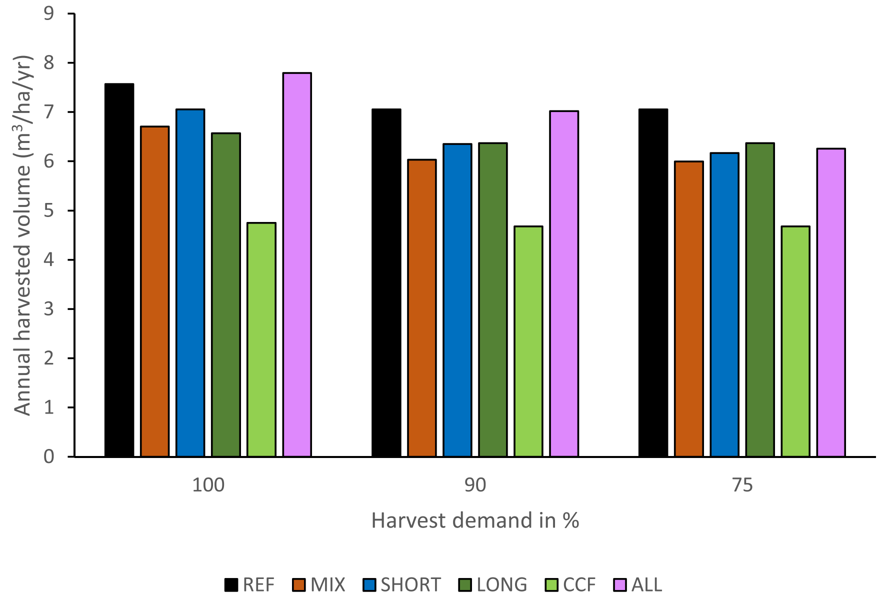


Fig. 5. Average annual harvested volume ($m^3ha^{-1}yr^{-1}$) for the management strategies during the 70-year planning horizon. In all management strategies (see Table 1 for detailed description), the objective was set to minimize the spruce bark beetle susceptibility index subject to a harvest demand and an even-flow constraint, except for the harvest demand of 100% that corresponded to the maximum achievable harvest volumes subject to an even-flow constraint.

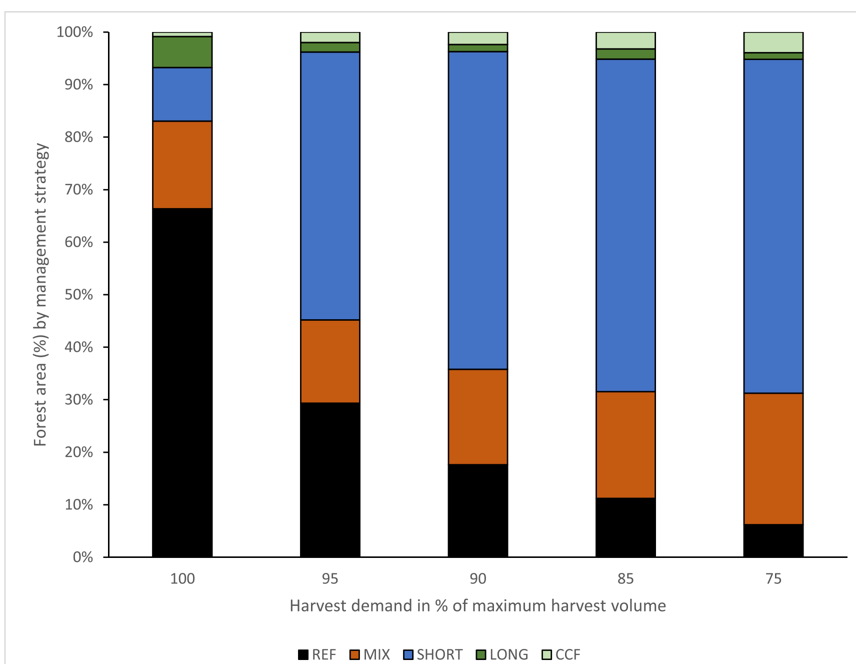


Fig. 6. Percentage of forest area that is subjected to each individual forest management strategy when the combined strategy (ALL) is applied. The distribution is shown for different harvest demands. See Table 1 for a description of forest management strategies.

3.4. Spruce bark beetle susceptibility index parameters

The development of the different parameters of the SBB susceptibility index during the planning horizon differed substantially between the strategies and the different HD scenarios (Fig. 7, Appendix F). The percentage of forest area with diameters greater than 20 cm (one of the conditions for the susceptibility index to show values other than zero) largely explains the differences between the susceptibility values obtained by the different strategies and for different HDs (Fig. 7A). For HD 100%, the REF, SHORT, and ALL strategies were the most successful in reducing the percentage of this area, translating into lower index values. On the other hand, when HD dropped to 90%, the differences in this percentage between the strategies became smaller. For HD 90%, the MIX strategy also became important by favouring the presence of other tree species at the expense of Norway spruce (Fig. 7).

Over the 70-year planning horizon, Norway spruce volumes were largest for the SHORT strategy and lowest for the MIX and CCF strategies (Fig. 7B, 7 F). In addition, birch volumes were favoured by the MIX strategy and also increased for the SHORT strategy (Fig. 7D). Basal area values for Norway spruce were relatively similar among the strategies (Fig. 7C, 7G). The average age of Norway spruce forest remained quite constant across all strategies (Appendix F). The SHORT and LONG

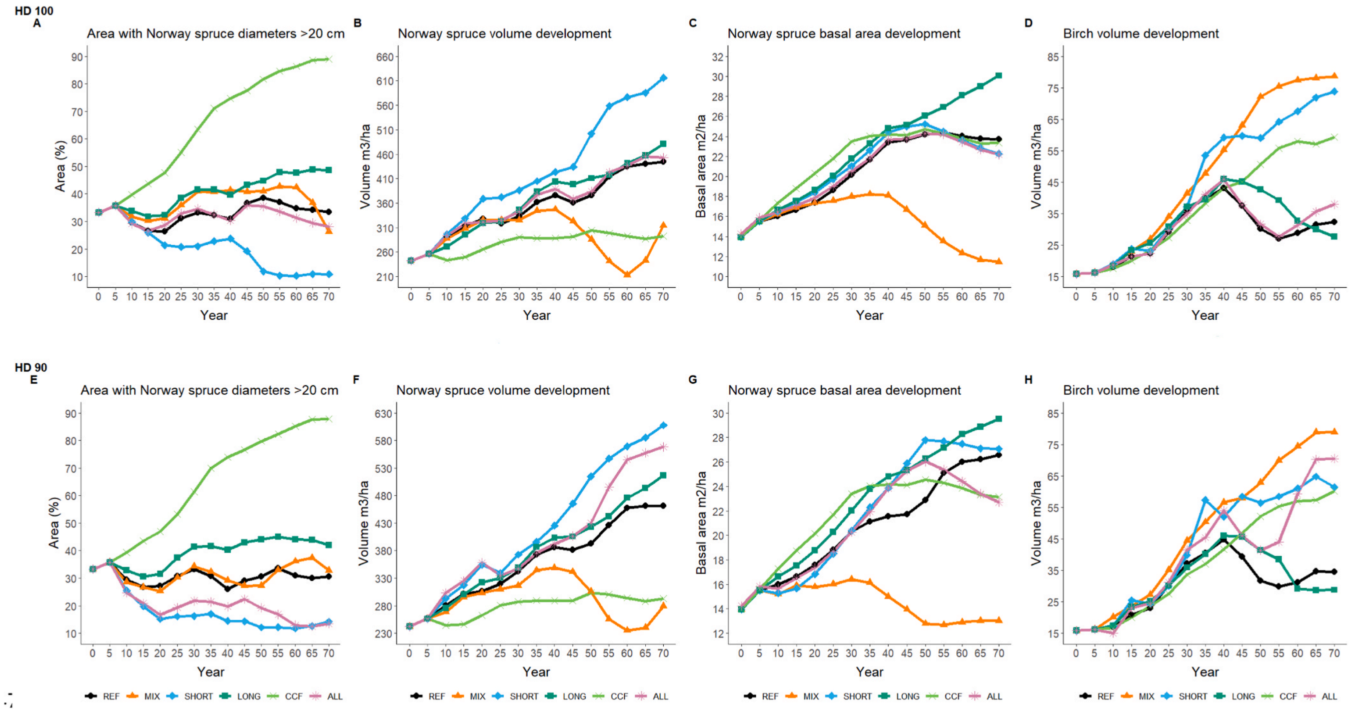


Fig. 7. SBB index parameter development over the 70-year planning horizon. The most important spruce bark beetle index parameters contributing to high values of susceptibility are presented in this figure for each of the strategies. These parameters are the Norway spruce dominated area with stem diameters over 20 cm (A), Norway spruce volume development (B), Norway spruce basal area development (C), and Birch volume development (D). HD 90 and 100% represent two different harvest demands. HD 100, is the maximum harvest that can be achieved subject to an even-flow harvest constraint.

strategies exhibited slightly lower and higher average ages, respectively, compared to the other strategies. Nonetheless, there were noticeable variations in average stem density among the different strategies with the SHORT strategy showing the highest densities, and the CCF strategy the lowest (Appendix F).

The results of HD 100% and HD 90% follow similar patterns for the forest parameters across strategies over the 70-year planning horizon (Fig. 7, Appendix F). For HD 90%, the MIX and ALL strategies presented the largest variations on Norway spruce and birch volumes compared to HD 100% (Figs. 7B, 7D). The MIX strategy resulted in a great reduction of Norway spruce volume and basal area in favour of birch trees. The effects of the MIX strategy were evident in the volume of birch trees, which increased substantially to more than twice by the end of the simulation period. However, the application of the MIX strategy did not lead to a substantial decrease in the proportion of Norway spruce forest area with stem diameters over 20 cm, which contributes largely to

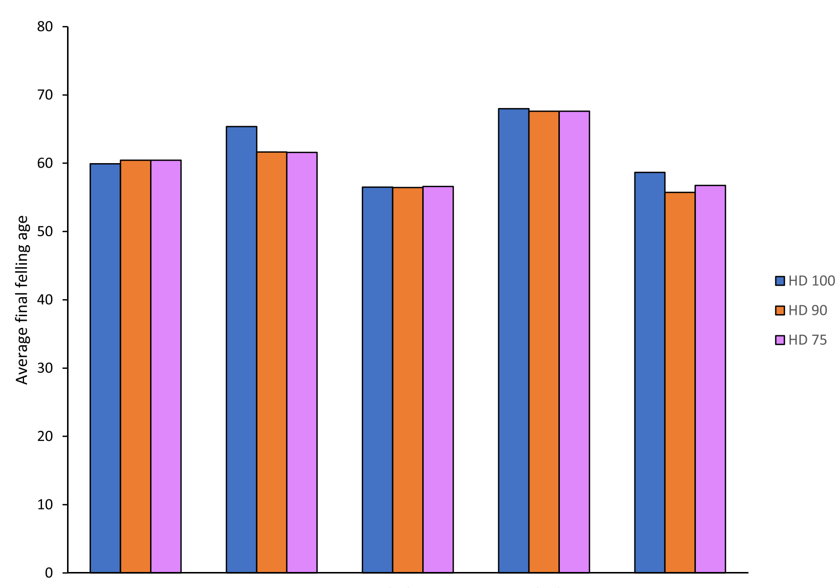


Fig. 8. Average final felling age for harvest demands (HD) 75, 90 and 100%, and for different forest management strategies. HD 100, HD 90, and HD 75 refer to harvest demands 100%, 90%, and 75%, respectively. HD 100 corresponds to the maximum achievable harvest volume subject to an even-flow constraint. See Table 1 for a description of forest management strategies.

higher susceptibility values (Fig. 7A). On the other hand, the ALL strategy showed a large decrease in the percentage of forest area with diameters over 20 cm as well as doubling the birch volume compared to HD 100%. In addition, the REF strategy continued to be associated with large Norway spruce average volumes per hectare and low birch volumes. In general, in the HD 90% scenario, the strategies showed lower proportions of forest area with diameters over 20 cm, and thus lower average SBB susceptibility values. In appendix G we show the development of the SBB index in relation to the volume of spruce >20 cm stem diameter in the landscape for the HD 90% scenario.

3.5. *Average final felling age and current annual increment*

The average final felling age ranged between 55 and 68 years across the strategies and did not differ markedly between harvest demand (Fig. 8). Both the REF and LONG strategies maintained a constant average final felling age with small variations for different harvest demands. Only the MIX and ALL strategies showed a minor reduction of 3–4 years in the average final felling age when harvest demands were lowered. The average final felling age was highest in the LONG strategy. The MIX strategy had the second-highest average final felling age, but the difference to the other strategies was small.

3.6. *Assessments of impacts of management strategies on biodiversity indicators*

Biodiversity indicators were assessed for harvest demands of 90 and 100% (Fig. 9 and Appendix C). In general, varying harvest demands did not impact the biodiversity indicators studied. However, management strategies did affect the development of biodiversity indicators over the planning horizon.

3.6.1. *Old forest*

The proportion of old forest remained low for all management strategies throughout the planning horizon regardless of harvest demand (Fig. 9.A).

3.6.2. *Mature broadleaf-rich forest*

The differences in forest area among the strategies were very small except for CCF, which had the largest proportion of mature broadleaf-rich forest, 40%, after 70 years of simulation (Fig. 9.B). In all other strategies, the proportion of mature broadleaf-rich forest changed only marginally throughout the 70-year planning horizon. The MIX and LONG strategies exhibited slightly higher values in the last 20 years of the planning horizon compared to REF, SHORT and ALL. The average percentage of mature broadleaf-rich forest was lowest in the SHORT strategy.

3.6.3. *Forest with large trees*

The forest area with large trees remained relatively constant at around 3% across all strategies except for CCF (Fig. 9.C). Under the CCF strategy, the percentage of forest area with large trees saw an increase to over 26% by the end of the planning horizon. The remaining strategies maintained their forest area with large trees within the range of 1–6%.

4. Discussion

The aim of our study is to assess how forest management strategies affect forest susceptibility to SBB over time and how the different strategies perform in relation to timber production demands and

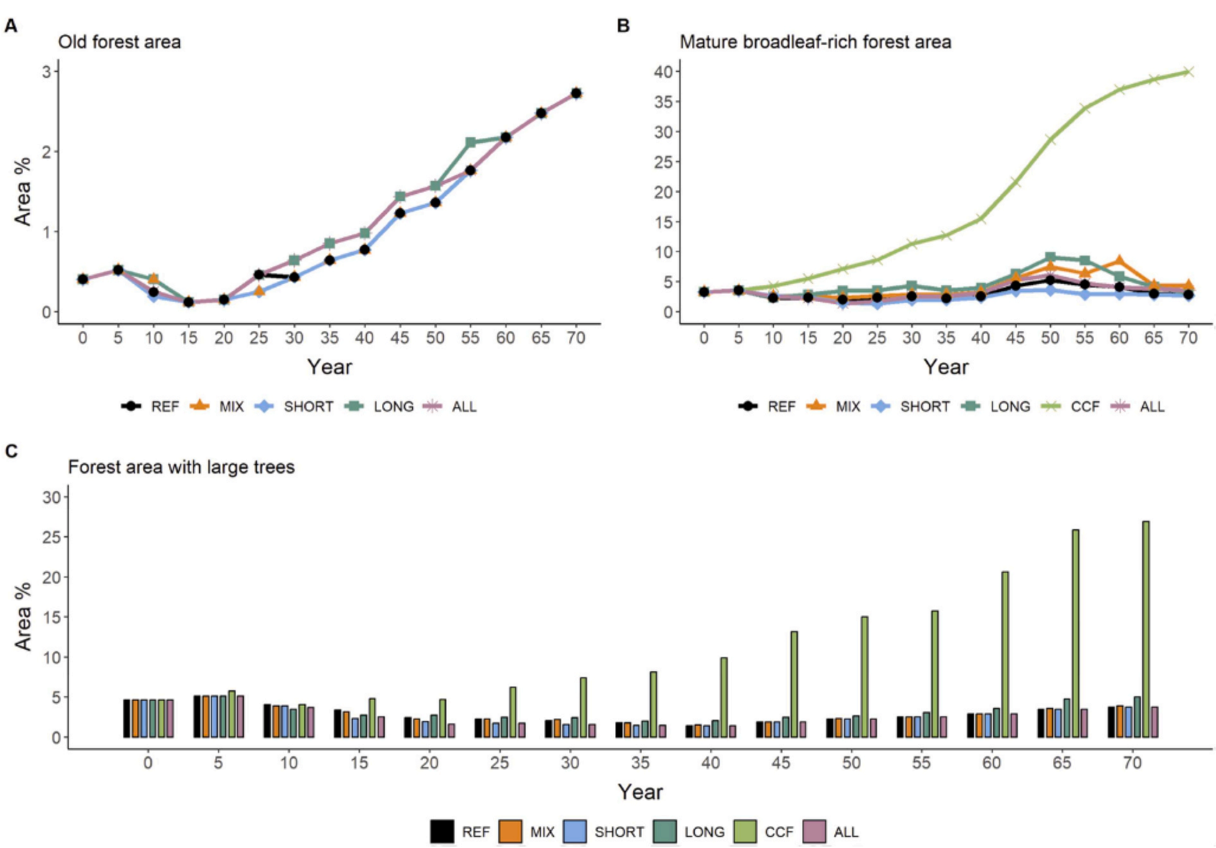


Fig. 9. Biodiversity indicators (related to the Swedish environmental quality objective Living Forests) development over the 70-year planning horizon for harvest demand 90%, A) old forest area, B) mature broadleaf-rich forest area, C) forest area with large trees of conifers and deciduous trees (stem diameter larger than 45 and 35 cm, respectively). A detailed description of of the forest management strategies is found in Table 1. In addition, a description of the biodivesity indicators is found in section 2.4 in the methods.

biodiversity. The average SBB susceptibility showed great differences among the management strategies. The management strategies that lead to the reduction of forest areas with mature Norway spruce trees were the most successful in lowering the average susceptibility value. Our results suggest that implementing multiple different strategies at the landscape level will be the most successful way to lower the average forest susceptibility to SBB damage while maintaining high harvest volumes. However, biodiversity indicators remained at a similar level in all management strategies except for the CCF strategy where the values increased.

4.1. Management implications on SBB susceptibility

The lowest average SBB susceptibility values were observed for the combined strategy, ALL, when minimizing the SBB index for different scenarios. Previous research also reported varying susceptibility levels when managing forests in different ways and for different purposes (e.g., Seidl et al. 2008; de Groot et al. 2018; Fora & Balog 2021). The SHORT strategy lowered the average Norway spruce forest age and reduced areas with Norway spruce stem diameters over 20 cm, resulting in low average susceptibility. The increased abundance of small-diameter trees did not increase susceptibility since SBB prefers large-diameter trees (≥20 cm) for breeding (Göthlin et al. 2000). In contrast, the LONG strategy increased the area of large-diameter Norway spruce trees, leading to higher susceptibility values over time.

Additionally, following the best performing strategies (ALL and SHORT), the REF and MIX strategies produced the third and fourth lowest average values of SBB susceptibility. Increasing tree mixtures in the forest while substantially reducing Norway spruce basal area in the MIX strategy brought down the average SBB index values to levels of those comparable to the REF strategy in the HD 90 scenario. As we approached the end of the planning horizon in our simulations, the MIX strategy markedly decreased average SBB index values. Hence, the beneficial effects of the MIX strategy can take several decades to be noticeable in the SBB susceptibility index but would then be most effective at the time an individual stand is at its most vulnerable. However, despite increasing the tree species mixture, Norway spruce still accounted for about 50% of basal area and thus had an important influence on average susceptibility due to the proportion of forest area with Norway spruce stem diameters over 20 cm.

On the other hand, the CCF strategy produced the highest values of susceptibility compared to all the other strategies and in all harvest demand scenarios. CCF was explored for managing susceptibility to SBB as the uneven-aged forest structure is thought to reduce susceptibility (Seidl et al. 2008; Björkman et al. 2015). However, in our study CCF resulted in high susceptibility values throughout the planning horizon. The CCF strategy did not fully eliminate susceptibility in a stand at any time as it did not reduce the overall presence of Norway spruce trees with stem diameters over 20 cm. This feature sets it apart from all other strategies, which experienced prolonged susceptibility-free periods after final harvests. These stands in the susceptibility-free period (i.e. SBB index = 0) reduce the overall average susceptibility value even though the stands that are in a susceptible period could return higher individual susceptibilities under the different management scenarios.

In addition, the CCF strategy that Heureka PlanWise simulated over time fell short of achieving a good uneven-aged structure, and this also affected the overall susceptibility result for this strategy. At the end of the planning horizon, approximately 85% of the forest area was dominated by Norway spruce trees with stem diameters over 20 cm contributing to high index values. The presence of regeneration and small diameter trees covered around 15% of the area resulting in a small proportion of forests with low susceptibility. A better performance of the CCF simulation might have given a larger proportion of forest in the regeneration phase and a greater reduction in the proportion of forest with large tree sizes. Nevertheless, CCF offers potential benefits, such as fostering tree species diversity and understory vegetation growth. It may also reduce susceptibility to SBB through sustained pressure from natural enemies (Klapwijk et al. 2016; Joelsson et al. 2018). These factors are not captured by the SBB susceptibility index.

Furthermore, the settings used in the definition of the management strategies played an important role on forest development and the parameters used to calculate the susceptibility index. Concerning the selection of management strategies in the ALL case, the way the management strategies were defined influenced the allocation of each management strategy in response to various harvest demand scenarios (Fig. 6). Those strategies resulting in greater reductions in the proportion of forest area dominated by Norway spruce with stem diameters above 20 cm were chosen at the expense of other strategies. The optimal share of management strategies for different scenarios was dominated by the REF, SHORT, and MIX strategies since the parameters that contributed the most to reducing the index value were especially favored by these strategies. On the one hand, the REF strategy was used largely when harvest demands were high since it performs the harvesting at the most economic advantageous age. In addition, the SHORT strategy, prevented the forest are from having mature forest areas dominated by Norway spruce with large diameters, producing large decreases on the SBB index. And the MIX strategy also contributed to decrease the proportion of Norway spruce in the forest by favouring the presence of other tree species.

4.2. Harvest demand influence on SBB susceptibility

Meeting higher harvest demands increased the average susceptibility to SBB. Large harvest demands involve finding the optimal rotation time, usually denoted by the intersection of mean annual volume increment (MAI) and current annual volume increment (CAI) curves. However, this often means allowing trees to grow for an extended period before harvesting, resulting in the presence of trees large enough for SBB colonization in the forest long before reaching the optimal rotation time. In this study, to minimize SBB susceptibility, the average final felling age decreased at the expense of maximum volume extraction. Choosing an earlier or later harvesting time affects the Norway spruce volume available for SBB colonization, which is crucial due to the correlation between large Norway spruce volumes and SBB infestation (Kärvemo et al. 2014). Reducing harvest demands narrows the susceptibility index gap between the management strategies. This also lowers the proportion of forest area with mean stem diameters exceeding 20 cm, reducing SBB susceptibility, aligning with previous research by Göthlin et al. (2000) and Kärvemo et al. (2014) on SBB colonization frequency related to stem diameters.

4.3. Implications for biodiversity

It is important to examine the impact that management strategies aiming to reduce SBB susceptibility might have on biodiversity. Regarding the proportion of forest area older than 120 years in the HD 100 and 90 scenarios, all strategies displayed modest upward trends. This is because average rotation times ranged between 55 and 68 years for all individual strategies. That is, even a 20% increase in the final felling age in the LONG strategy didn't raise the average forest age enough to positively impact this biodiversity indicator. However, longer simulations than the ones applied in this study to increase the proportion of older forests might have allowed set-asides to reach the required 120 years, making a larger contribution to this indicator. Regarding the mature broadleaf-rich forest, the observed trend was similar to the old forest indicator. Again, rotation times ranging between 55 and 68 years influenced the development of the forest and prevented it from meeting the criteria for a mature broadleaf-rich forest. The inclusion of biodiversity parameters demands in the optimization model could have improved the outcomes across management strategies, for example through choosing treatment schedules that retain more broadleaf trees during practices like precommercial thinning or commercial thinnings and extended rotation times. Also, the share of each management strategy chosen for a given harvest demand while minimizing the spruce bark beetle susceptibility index value in the ALL case could have varied. For instance, CCF might have been selected to be applied to a larger share of the forest since it was successful in increasing mature broadleaf-rich forests and areas with large trees. Major differences in the results for large-diameter trees were obtained, indicating that strategies that implement clearcuts are associated with reduced susceptibility to SBB, whereas strategies excluding clearcuts show higher susceptibility to SBB.

4.4. Uncertainties and computational limitations

It's important to acknowledge underlying uncertainties in the analyses, as the results provide an initial assessment of how management strategies affect susceptibility to SBB and the associated trade-offs with timber production and biodiversity implications. The estimation of relative SBB susceptibility of the forest is a measure that depends entirely on how the index is constructed, what forest variables are included, and their weight (Nordkvist et al. 2023). Although the included variables represent key forest characteristics empirically related to SBB damage, the index does not consider extreme weather events like drought or other disturbances that could impact forest health and thus susceptibility. However, the index still offers valuable insights, though the assessment of results requires an understanding of these limitations.

Additionally, the SBB index was initially designed for stand-level use. In this study, we calculated the average value for each of the national forest inventory plots in the county to compare forest susceptibility across management strategies at the county level. The use of the SBB index on plot level has a larger spread in forest attributes compared to stand mean attributes where the variability or spread in measurements is not as pronounced. The way the index is composed makes temperature sum, Norway spruce volume, and Norway spruce stem diameter the most important variables contributing to susceptibility, which explains the modest impact of the MIX strategy and the high impact of the SHORT strategy. Thus, the conclusions drawn from the results may have been influenced by the construction and the use of the index. On the other hand, it is reasonable to assume that management strategies with higher susceptibility may result in greater damage, which in turn will affect timber production and biodiversity. However, the quantification of these impacts is beyond the scope of this study.

The Heureka system has uncertainties in conducting forest growth development simulations, acknowledging that models are inherently imperfect. Heureka growth models are primarily built on data collected from even-aged forests, making simulations for uneven-aged forestry (CCF) less certain compared to other strategies. It is important to acknowledge that Heureka's simulations of growth development are approximations and not exact measurements of how the forest will look like in the coming years. Therefore, interpreting results should be approached as indications of change rather than a precise prediction of future outcomes.

One aspect of SBB damage dynamics that is hard to predict is the level of damage in the endemic phase, epidemic phase, and how to reduce the risk of start of an outbreak either following storm damage or a prolonged period of drought. As SBB is dependent on the volume of spruce in the right size category in the landscape (see appendix G), all management that reduce the available resource for SBB will have an impact on the overall susceptibility to spruce bark beetle damage. Variation in the landscape will most likely reduce the risk of large-scale spruce bark beetle outbreaks, and reduce the risk of large stand-level losses.

5. Conclusions

Our findings suggest that various management strategies can effectively reduce the susceptibility of forests to damage caused by SBB. Among the management strategies studied, the combined strategy referred to as "ALL" proved to be the best strategy to maximize harvested volumes and reduce susceptibility for SBB. This result is in line with other studies, suggesting that diversity-oriented forestry is generally good to spreading the risk and reducing the forest susceptibility to damage at landscape level. In contrast, the CCF strategy consistently showed high susceptibility values throughout the entire planning horizon when compared to the other strategies. In addition, our results suggest that the most effective way to decrease susceptibility to SBB through management is by reducing the abundance of large Norway spruce trees in the forest. Therefore, it seems reasonable to prioritize management efforts aimed at creating forest conditions that target this specific aspect. However, the need to balance different management objectives simultaneously such as SBB susceptibility, timber production and biodiversity may require specific measures beyond the ones that were implemented in this study. It is also essential to recognize that forests are slow-growing systems. To see positive impacts from implementing management strategies such as MIX (to increase the proportion of broadleaves at the expense of conifers) requires time, which emphasizes the need to think ahead and create resilient ecosystems that are adapted to an increasingly uncertain future.

CRediT authorship contribution statement

Teresa López-Andújar Fustel: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Methodology, Formal analysis, Conceptualization. **Michelle Nordkvist:** Writing – review & editing, Supervision, Methodology. **Karin Öhman:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Maartje Klapwijk:** Writing – review & editing, Supervision, Methodology. **Jeannette Eggers:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Lars Sängstuvall:** Writing – review & editing, Supervision, Methodology. **Tomas Lämås:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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.

Data Availability

The authors do not have permission to share data.

Acknowledgements

The Swedish research council FORMAS 2021-02132. The Forest Damage Center (SLU Skogsskadecentrum) 2022-51-18.

Appendix

A. Mathematical algorithm to maximize harvest volume

The mathematical formulation to maximize the harvested volume over the planning horizon has the following equations, Eq. A1 is the objective function that maximizes harvested volume over the planning horizon, Eqs. A2 and A3 are constraints that ensure an even flow of harvested timber over the planning horizon (Eq. A2 is the lower bound and Eq. A3 is the upper bound), and Eqs. A4 and A5 ensure that all plots are assigned a treatment schedule.

$$Max\ MVH = \sum_{i=1}^{I}\sum_{j=1}^{J_i}\sum_{p=1}^{P} a_i x_{ij} v_{ijp} \tag{A1}$$

subject to,

$$\sum_{i=1}^{I}\sum_{j=1}^{J_i} v_{ij(p+1)} x_{ij} a_i \geq (1-\alpha)\sum_{i=1}^{I}\sum_{j=1}^{J_i} v_{ijp} x_{ij} a_i \quad \forall p \in P-1 \tag{A2}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J_i} v_{ij(p+1)} x_{ij} a_i \leq (1+\alpha)\sum_{i=1}^{I}\sum_{j=1}^{J_i} v_{ijp} x_{ij} a_i \quad \forall p \in P-1 \tag{A3}$$

$$\sum_{j=1}^{J_i} x_{ij} = 1 \quad \forall i \in I \tag{A4}$$

$$0 \leq x_{ij} \leq 1 \quad \forall i \in I, \quad \forall j \in Ji \tag{A5}$$

where:

i is a plot contained in the set of plots I, j is a treatment schedule contained in the set of treatments schedules J_i for plot i, p is a period contained in the set of periods P of the planning horizon, and a_i is the forest area in hectares that plot i represents in the county, x_{ij} is a continuous decision variable that takes a value between 0 and 1 depending on the proportion of area of plot i that is assigned to treatment schedule j, v_{ijp} is the volume harvested in plot i, treatment schedule j and period p, α is a parameter that establishes the maximum allowed deviation of harvested volume between consecutive periods and was set to 0.2.

B. Mathematical algorithm to minimize SBB susceptibility index

The mathematical formulation of the problems is as follows where Eq. A1 is the objective function that minimizes the SBB susceptibility index value over the planning horizon, Eqs. A2 and A3 are constraints that ensure that an even-flow harvest of timber over the planning horizon is obtained (Eq. A2 is the lower bound and Eq. A3 is the upper bound), Eq. A4 is the constraint that ensures a minimum volume of harvest relative to maximize harvest volume for every optimization problem, and Eq. A5 and A6 ensure that all forest plots are assigned a treatment schedule.

$$Min\ Z = \sum_{i=1}^{I}\sum_{j=1}^{J_i}\sum_{p=1}^{P} a_i x_{ij} B_{ijp} \tag{B1}$$

subject to,

$$\sum_{i=1}^{I}\sum_{j=1}^{J_i} v_{ij(p+1)} x_{ij} a_i \geq (1-\alpha)\sum_{i=1}^{I}\sum_{j=1}^{J_i} v_{ijp} x_{ij} a_i \quad \forall p \in P-1 \tag{B2}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J_i} v_{ij(p+1)} x_{ij} a_i \leq (1+\alpha)\sum_{i=1}^{I}\sum_{j=1}^{J_i} v_{ijp} x_{ij} a_i \quad \forall p \in P-1 \tag{B3}$$

$$\sum\nolimits_{i=1}^{I}\sum\nolimits_{j=1}^{J_i}\sum_{p}^{P} a_i x_{ij} v_{ijp} \geq \beta * MaximumHarvestVolume \tag{B4}$$

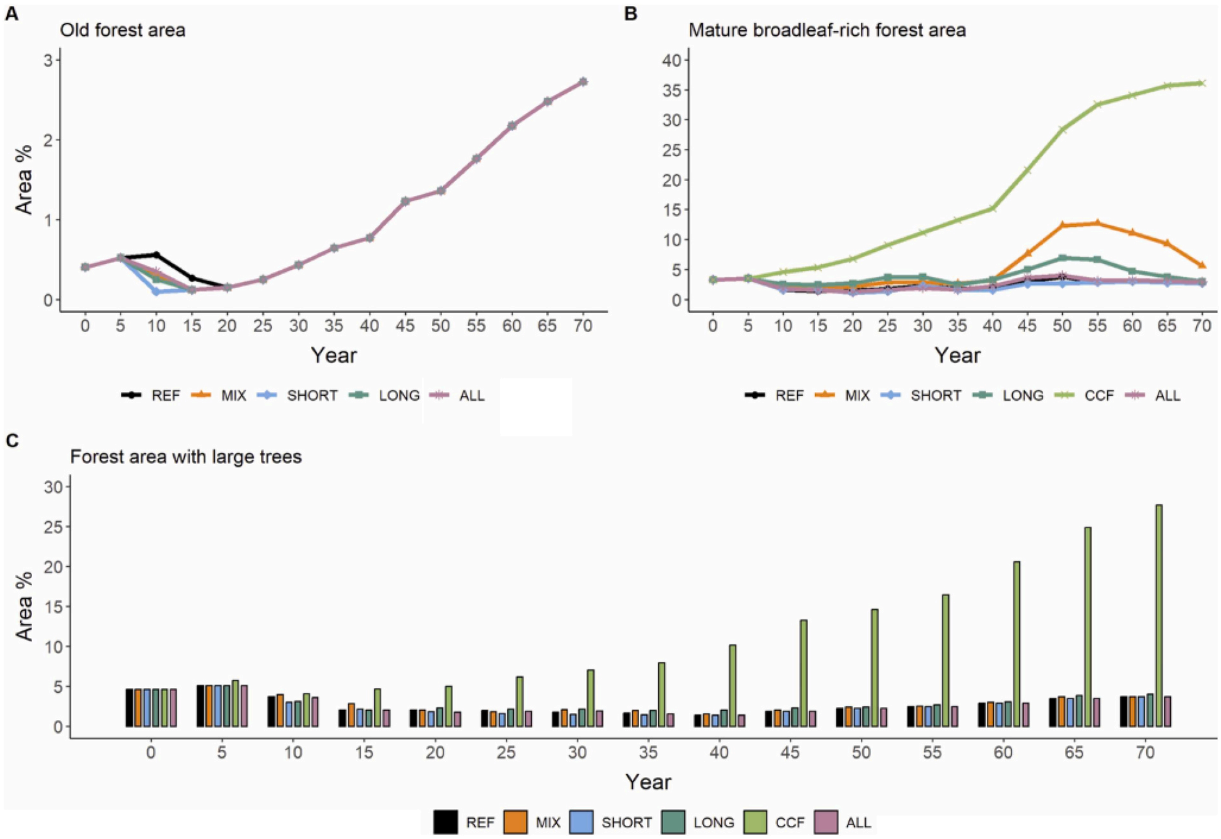
$$\sum_{j=1}^{J_i} x_{ij} = 1 \quad \forall i \in I \tag{B5}$$

$$0 \leq x_{ij} \leq 1 \quad \forall i \in I, \quad \forall j \in Ji \tag{B6}$$

where:

i is a plot contained in the set of plots I, j is a treatment schedule contained in the set of treatments schedules J_i for plot i, p is a period contained in the set of periods P of the planning horizon, and a_i is the forest area in hectares that plot i represents in the county, x_{ij} is a continuous decision variable that takes a value between 0 and 1 subject to the proportion of area of plot i that is assigned to treatment schedule j, B_{ijp} is the spruce bark beetle susceptibility index value for plot i, treatment schedule j and period p, v_{ijp} is the harvested volume for plot i, treatment schedule j and period p, α is a parameter that establishes the maximum allowed deviation of harvested volume between consecutive periods and was set to 0.2, β is a parameter that establishes the minimum percentage of timber that should be harvested in the optimization problem, maximum harvested volume is a parameter that establishes the maximum volume that could be harvested for each optimization problem if the objective was set to maximize harvested volume without consideration to the spruce bark beetle susceptibility index. To estimate this parameter value, we used the algorithm described in Appendix A.

C. Biodiversity indicators for Harvest Demand 100



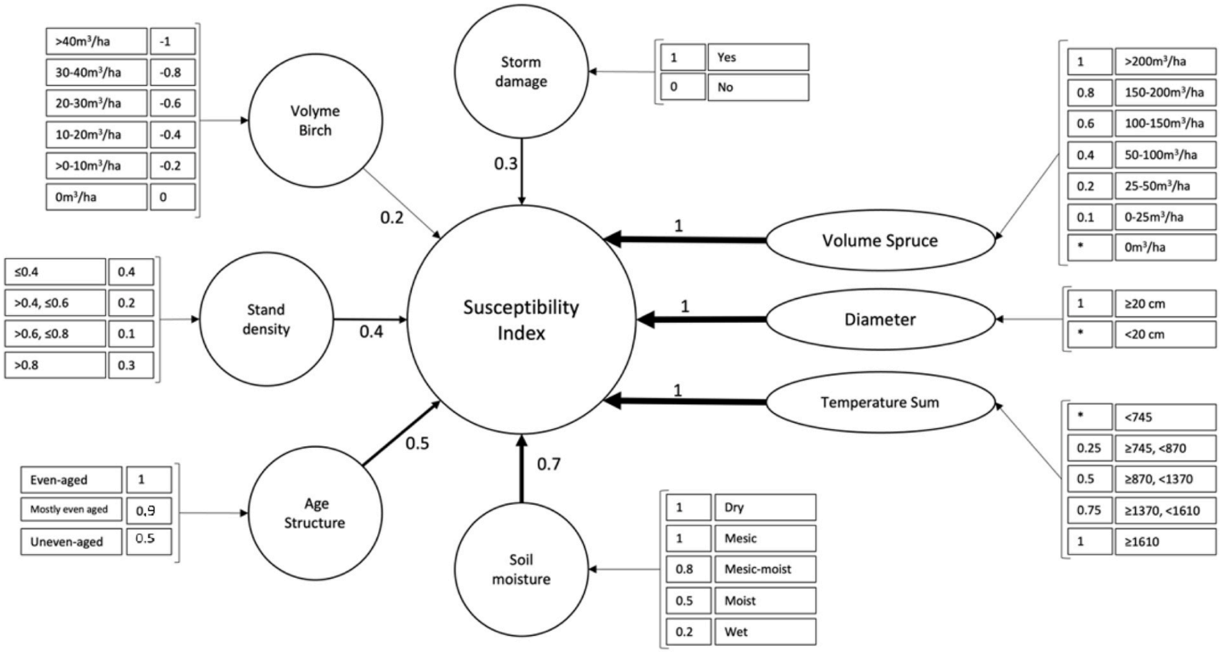
Development of biodiversity indicators over the planning horizon for harvest demand 100%, A) old forest area, B) mature broadleaf forest area, and C) average number of large trees of conifers and deciduous trees. See Table 1 for a detailed description of the management strategies.

D. Detailed description of the five management strategies

The *Reference* strategy was designed to resemble current practical forestry in Sweden. The description of the other four strategies below highlights how they differ from the reference strategy.

- *Reference strategy* (REF). Regeneration of the forest was performed by planting Norway spruce seedlings after final felling. The number of seedlings that were planted per hectare that were planted depended on site index. Soil preparation was also implemented before the planting of seedlings. Precommercial thinning was then carried out when trees were between 2 and 6 m high giving a higher weight to removing tree species different from Norway spruce. Thinnings were performed two or three times during the rotation period, but before tree heights exceeded 20 m. In addition, we simulated the retention of 10 trees per hectare and 3 high stumps per hectare after final felling, and a set aside of 10% of the forest area that was harvested. As exception, after final felling in dry soil types, Scots pine (*Pinus sylvestris* L.) seedlings were planted instead of Norway spruce. In all other sites, the tree species chosen for regeneration was the dominant species before final felling.
- *Mixed forest strategy* (MIX). Same as REF but:
  - o at regeneration, only 1200 seedlings per hectare were planted independently of site index to allow for incoming natural regeneration of other tree species such as silver birch (*Betula pendula* L.) or downy birch (*Betula pubescens* Ehrh.).
  - o after pre-commercial and commercial thinnings, 40% of stems should be birch and other non- Norway spruce stems if possible.
- *Short rotation without thinnings* (SHORT). Same as REF but:
  - o no thinnings were allowed.
  - o minimum final felling age was lowered by 10% from the minimum allowed final felling age stated in the Swedish Forestry Act. In addition, a maximum delay on the execution of the final felling was set to 15 years.
- *Long rotation* (LONG). Same as REF but:
  - o minimum final felling age was increased by 20% from the minimum allowed final felling age stated in the Swedish Forestry Act. In addition, a maximum delay on the execution of the final felling was set to 50 years.
- *Continuous cover forestry* (CCF). In this strategy, final fellings were not performed and the removal of timber from the forest was carried out by a series of selection fellings, implemented as thinnings from above. At the time of harvest, a higher weight was given to conifers over deciduous trees, Norway spruce over Scots pine and to large stem diameter trees over small trees.

E. Detailed description of how the SBB susceptibility index is calculated



The spruce bark beetle (SBB) susceptibility index, as presented by Nordkvist et al. 2023, is constructed from separate variables found to contribute to the susceptibility of SBB attacks. Each variable (represented by circles and ovals) is comprised of different factors (rectangles), each assigned a corresponding weight reflecting its contribution to the overall index. These variable weights range from 1 (highest) to close to zero (lowest), or zero itself, with values indicated next to the respective factors. The variable weights are located next to the arrows. An asterisk denotes that when a variable has that value, the entire index automatically resets to zero, i.e., no susceptibility. The calculation involves multiplying the variable's value by the variable's weight, and then summing these values for each variable to give the final susceptibility index value.

The susceptibility index has a maximum value of 3.66, indicating conditions where there is no birch in the plot, the plot is open i.e., not dense, had an even-age structure, was situated on either dry or mesic soils, had no storm damage, a Norway spruce volume exceeding 200 m^3/ha, and temperature sum conducive to two generations each growing season. On the contrary, when the index value is not zero, the minimum achievable value for the index is 0.58. This minimum index value of 0.58 indicates a stand characterized by a density of over 40 m^3/ha of birch, an intermediate stand density ranging between 0.6 and 0.8, an uneven-age structure, wet soils, no storm occurrence, Norway spruce volume varying from 0 to 25 m^3/ha, and temperature sum conditions that allow the completion of one generation only in favourable years. If Norway spruce is not present in a plot or if Norway spruce trees mean stem diameters are less than 20 cm or if the temperature sum for completing one generation is not reached, the index susceptibility value will be zero. In Heureka, the temperature sum is constant and is calculated based on historical data for the study area. In this study, the simulation of storm damage was not applied and therefore not accounted for in the calculation of the index.

F. Development of SBB index parameters

Mean values for the forest of Kronoberg country and each management strategy on different year periods are presented for the following parameters: mean age of the forest, number of Norway spruce stems, stand canopy closure and mean spruce bark beetle (SBB) index values. The numbers provided show the comparison between the initial state of the forest, first row (grey), and the average values for the whole 70-year planning horizon (blue), as well as the average for two other time periods, 0–20 (yellow) and 50–70 years (green). The results are shown for harvest demands 100 and 90% (harvest demand 100% is the maximum harvest that one can achieve subject to an even-flow harvest constraint). Mean age for the CCF strategy (i.e., uneven aged forest management) not provided as the calculated forest age in this case is not directly comparable with ages for the other even-aged forest management strategies. The forest management strategies are explained in detail in Table 1.

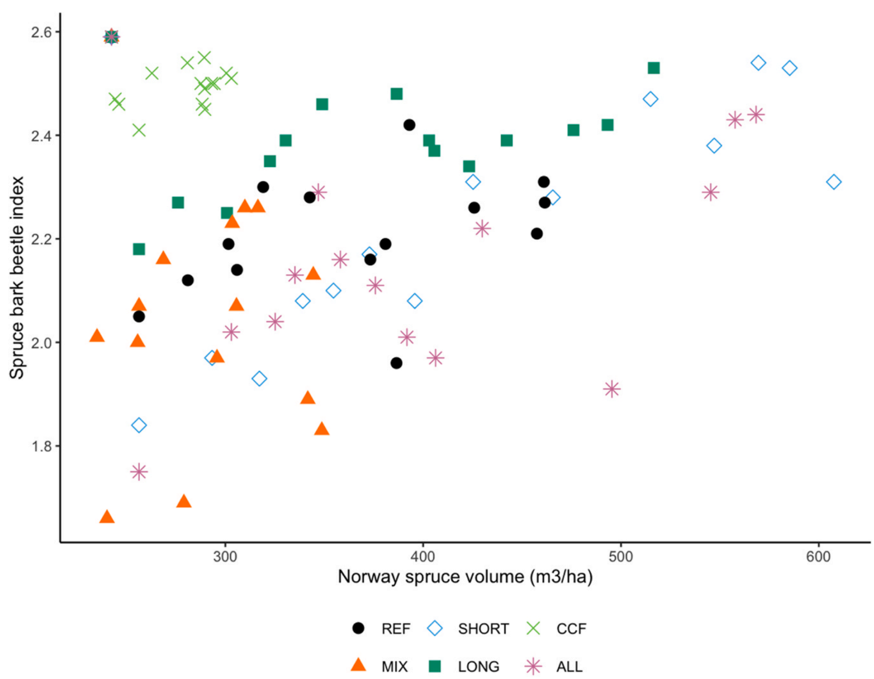
Harvest demand (%)	Management strategy	Year period	Mean age (yr)	Norway spruce stem density (st/ha)	Closure	Mean SBB index
-	-	0	36	1704	0.6	0.86
100	REF	1 – 70	36	2027	0.8	0.94
100	MIX	1 – 70	38	1511	0.7	1.05
100	SHORT	1 – 70	34	2358	0.8	0.76
100	LONG	1 – 70	40	1829	0.8	1.14
100	CCF	1 – 70	-	970	0.7	1.64
100	ALL	1 – 70	35	2051	0.8	0.93
90	REF	1 – 70	36	2051	0.8	0.82

(*continued on next page*)

(*continued*)

Harvest demand (%)	Management strategy	Year period	Mean age (yr)	Norway spruce stem density (st/ha)	Closure	Mean SBB index
90	MIX	1 – 70	36	1536	0.7	0.86
90	SHORT	1 – 70	35	2376	0.9	0.60
90	LONG	1 – 70	40	1863	0.8	1.05
90	CCF	1 – 70	-	977	0.7	1.60
90	ALL	1 – 70	35	2293	0.8	0.61
100	REF	1 – 20	34	1967	0.7	0.76
100	MIX	1 – 20	36	1734	0.7	0.85
100	SHORT	1 – 20	34	2052	0.8	0.72
100	LONG	1 – 20	37	1806	0.7	0.84
100	CCF	1 – 20	-	1373	0.7	1.06
100	ALL	1 – 20	34	1969	0.8	0.77
90	REF	1 – 20	36	1926	0.7	0.71
90	MIX	1 – 20	35	1806	0.6	0.74
90	SHORT	1 – 20	33	2168	0.8	0.59
90	LONG	1 – 20	37	1818	0.7	0.82
90	CCF	1 – 20	-	1374	0.7	1.04
90	ALL	1 – 20	33	2152	0.8	0.58
100	REF	51 – 70	36	2180	0.9	1.07
100	MIX	51 – 70	37	1483	0.6	1.03
100	SHORT	51 – 70	33	2744	0.9	0.86
100	LONG	51 – 70	44	1843	0.9	1.40
100	CCF	51 – 70	-	583	0.7	2.18
100	ALL	51 – 70	35	2225	0.9	1.01
90	REF	51 – 70	38	2129	0.9	0.87
90	MIX	51 – 70	38	1260	0.7	0.90
90	SHORT	51–70	37	2604	1.0	0.64
90	LONG	51–70	43	1945	0.9	1.18
90	CCF	51–70	-	593	0.7	2.15
90	ALL	51–70	36	2550	0.9	0.60

G. Relationship between volume of Norway spruce and spruce bark beetle susceptibility index



The figure shows the relationship between volume of Norway spruce (mean stand stem diameter >20 cm) and the values of the SBB index in the landscape for all six management scenarios. The points represent an outcome of the SBB index and the spruce volume in any of the five-year periods in the 70-year projections.

References

Andersson, C., Karlsson, S., Andersson, E., Roberge, J.-M., Österdahl, S., Flygar, T. & Svensson, D. (2022). *Levande skogar: Fördjupad utvärdering.* (Levande skogar, 2022/12). Skogsstyrelsen.

Berg, E.E., David Henry, J., Fastie, C.L., De Volder, A.D., Matsuoka, S.M., 2006. Spruce beetle outbreaks on the Kenai Peninsula, Alaska, and Kluane National Park and Reserve, Yukon Territory: relationship to summer temperatures and regional differences in disturbance regimes. For. Ecol. Manag. 227 (3), 219–232. https://doi.org/10.1016/j.foreco.2006.02.038.

Björkman, C., Bylund, H., Nilsson, U., Nordlander, G., Schroeder, M., 2015. Effects of new forest management on insect damage risk in a changing climate. Eff. N. For. Manag. Insect Damage risk a Chang. Clim. 7, 248–266. ⟨https://www.cabidigitallibrary.org/doi/epdf/10.1079/9781780643786.0248?src=getftr [2023-10-10]⟩.

Christiansen, E., Bakke, A., 1988. The spruce bark beetle of eurasia. In: Berryman, A.A. (Ed.), Dynamics of forest insect populations: patterns, causes, implications. Springer US, pp. 479–503. https://doi.org/10.1007/978-1-4899-0789-9_23.

Dutilleul, P., Nef, L., Frigon, D., 2000. Assessment of site characteristics as predictors of the vulnerability of Norway spruce (*Picea abies Karst.*) stands to attack by *Ips typographus* L. (Col., Scolytidae). J. Appl. Entomol. 124 (1), 1–5. https://doi.org/10.1046/j.1439-0418.2000.00440.x.

Faccoli, M., Bernardinelli, I., 2014. Composition and elevation of spruce forests affect susceptibility to bark beetle attacks: implications for forest management. Forests 5 (1), 88–102. https://doi.org/10.3390/f5010088.

Fahlvik, N., Agestam, E., Nilsson, U., Nyström, K., 2005. Simulating the influence of initial stand structure on the development of young mixtures of Norway spruce and birch. For. Ecol. Manag. 213 (1), 297–311. https://doi.org/10.1016/j.foreco.2005.03.021.

Fridman, J., Holm, S., Nilsson, M., Nilsson, P., Ringvall, A.H., Ståhl, G., 2014. Adapting national forest Inventories to changing requirements – the case of the swedish national forest inventory at the turn of the 20th century. Silva Fenn. 48 (3). ⟨https://www.silvafennica.fi/article/1095 [2023-12-05]⟩.

Fritscher, D., Schroeder, M., 2022. Thermal sum requirements for development and flight initiation of new-generation spruce bark beetles based on seasonal change in cuticular colour of trapped beetles. Agric. For. Entomol. 24 (3), 405–421. https://doi.org/10.1111/afe.12503.

Göthlin, E., Schroeder, L.M., Lindelöw, A., 2000. Attacks by *Ips typographus* and *Pityogenes chalcographus* on windthrown spruces (*Picea abies*) during the two years following a storm felling. Scand. J. For. Res. 15 (5), 542–549. https://doi.org/10.1080/028275800750173492.

GrÉGoire, J.-C., Evans, H.F., 2004. Damage and control of bawbilt organisms an overview. In: Lieutier, F., Day, K.R., Battisti, A., Grégoire, J.-C., Evans, H.F. (Eds.), Bark and Wood Boring Insects in Living Trees in Europe, a Synthesis. Springer Netherlands, pp. 19–37. https://doi.org/10.1007/978-1-4020-2241-8_4.

de Groot, M., Ogris, N., Kobler, A., 2018. The effects of a large-scale ice storm event on the drivers of bark beetle outbreaks and associated management practices. For. Ecol. Manag. 408, 195–201. https://doi.org/10.1016/j.foreco.2017.10.035.

de Groot, M., Ogris, N., Diaci, J., Castagneyrol, B., 2023. When tree diversity does not work: The interacting effects of tree diversity, altitude and amount of spruce on European spruce bark beetle outbreaks. For. Ecol. Manag. 537, 120952 https://doi.org/10.1016/j.foreco.2023.120952.

Jactel, H., Bauhus, J., Boberg, J., Bonal, D., Castagneyrol, B., Gardiner, B., Gonzalez-Olabarria, J.R., Koricheva, J., Meurisse, N., Brockerhoff, E.G., 2017. Tree diversity drives forest stand resistance to natural disturbances. Curr. For. Rep. 3 (3), 223–243. https://doi.org/10.1007/s40725-017-0064-1.

Joelsson, K., Hjältén, J., Work, T., 2018. Uneven-aged silviculture can enhance within stand heterogeneity and beetle diversity. J. Environ. Manag. 205, 1–8. https://doi.org/10.1016/j.jenvman.2017.09.054.

Jönsson, A.M., Appelberg, G., Harding, S., Bärring, L., 2009. Spatio-temporal impact of climate change on the activity and voltinism of the spruce bark beetle, *Ips typographus*. Glob. Change Biol. 15 (2), 486–499. https://doi.org/10.1111/j.1365-2486.2008.01742.x.

Jönsson, A.M., Bärring, L., 2011. Future climate impact on spruce bark beetle life cycle in relation to uncertainties in regional climate model data ensembles, 63 (1), 158–173. https://doi.org/10.1111/j.1600-0870.2010.00479.x.

Jönsson, A.M., Harding, S., Krokene, P., Lange, H., Lindelow, A., Okland, B., Ravn, H.P., Schroeder, L.M., 2011. Modelling the potential impact of global warming on *Ips typographus* voltinism and reproductive diapause. Clim. Change 109 (3–4), 695–718. https://doi.org/10.1007/s10584-011-0038-4.

Jönsson, A.M., Lagergren, F., Smith, B., 2015. Forest management facing climate change - an ecosystem model analysis of adaptation strategies. Mitig. Adapt. Strateg. Glob. Change 20 (2), 201–220. https://doi.org/10.1007/s11027-013-9487-6.

Kärvemo, S., Johansson, V., Schroeder, M., Ranius, T., 2016. Local colonization-extinction dynamics of a tree-killing bark beetle during a large-scale outbreak. Ecosphere 7 (3).

Kärvemo, S., Rogell, B., Schroeder, M., 2014. Dynamics of spruce bark beetle infestation spots: Importance of local population size and landscape characteristics after a storm disturbance. For. Ecol. Manag. 334, 232–240. https://doi.org/10.1016/j.foreco.2014.09.011.

Klapwijk, M.J., Bylund, H., Schroeder, M., Björkman, C., 2016. Forest management and natural biocontrol of insect pests. For.: Int. J. For. Res. 89 (3), 253–262. https://doi.org/10.1093/forestry/cpw019.

Komonen, A., Schroeder, L.M., Weslien, J., 2011. *Ips typographus* population development after a severe storm in a nature reserve in southern Sweden. J. Appl. Entomol. 135 (1–2), 132–141. https://doi.org/10.1111/j.1439-0418.2010.01520.x.

Lämås, T., Sängstuvall, L., Öhman, K., Lundström, J., Årevall, J., Holmström, H., Nilsson, L., Nordström, E.-M., Wikberg, P.-E., Wikström, P., Eggers, J., 2023. The multi-faceted Swedish Heureka forest decision support system: context, functionality, design, and 10 years experiences of its use. Front. For. Glob. Change 6. ⟨https://www.frontiersin.org/articles/10.3389/ffgc.2023.1163105 [2023-10-10]⟩.

Müller, M., Olsson, P.-O., Eklundh, L., Jamali, S., Ardö, J., 2022. Features predisposing forest to bark beetle outbreaks and their dynamics during drought. For. Ecol. Manag. 523, 120480 https://doi.org/10.1016/j.foreco.2022.120480.

Netherer, S., Hammerbacher, A., 2022. 4 - The Eurasian spruce bark beetle in a warming climate: Phenology, behavior, and biotic interactions. In: Gandhi, K.J.K., Hofstetter, R.W. (Eds.), Bark Beetle Management, Ecology, and Climate Change. Academic Press, pp. 89–131. https://doi.org/10.1016/B978-0-12-822145-7.00011-8.

Netherer, S., Nopp-Mayr, U., 2005. Predisposition assessment systems (PAS) as supportive tools in forest management—rating of site and stand-related hazards of bark beetle infestation in the High Tatra Mountains as an example for system application and verification. For. Ecol. Manag. 207 (1), 99–107. https://doi.org/10.1016/j.foreco.2004.10.020.

Nordkvist, M., Eggers, J., Fustel, T.L.-A., Klapwijk, M.J., 2023. Development and implementation of a spruce bark beetle susceptibility index: a framework to compare bark beetle susceptibility on stand level. Trees, For. People 11, 100364. https://doi.org/10.1016/j.tfp.2022.100364.

Overbeck, M., Schmidt, M., 2012. Modelling infestation risk of Norway spruce by *Ips typographus (L.)* in the Lower Saxon Harz Mountains (Germany). For. Ecol. Manag. 266, 115–125. https://doi.org/10.1016/j.foreco.2011.11.011.

Romashkin, I., Neuvonen, S., Tikkanen, O.-P., 2020. Northward shift in temperature sum isoclines may favour *Ips typographus* outbreaks in European Russia. Agric. For. Entomol. 22 (3), 238–249. https://doi.org/10.1111/afe.12377.

Schelhaas, M.-J., 2008. Impacts of natural disturbances on the development of European forest resources: application of model approaches from tree and stand levels to large-scale scenarios. Diss. For. 2008 (56) https://doi.org/10.14214/df.56.

Schroeder, L.M., Lindelöw, Å., 2002. Attacks on living spruce trees by the bark beetle *Ips typographus* (Col. Scolytidae) following a storm-felling: a comparison between stands with and without removal of wind-felled trees. Agric. For. Entomol. 4 (1), 47–56. https://doi.org/10.1046/j.1461-9563.2002.00122.x.

Seidl, R., Baier, P., Rammer, W., Schopf, A., Lexer, M.J., 2007. Modelling tree mortality by bark beetle infestation in Norway spruce forests. Ecol. Model. 206 (3), 383–399. https://doi.org/10.1016/j.ecolmodel.2007.04.002.

Seidl, R., Rammer, W., Jaeger, D., Lexer, M.J., 2008. Impact of bark beetle (*Ips typographus L.*) disturbance on timber production and carbon sequestration in different management strategies under climate change. For. Ecol. Manag. 256 (3), 209–220. https://doi.org/10.1016/j.foreco.2008.04.002.

Seidl, R., Schelhaas, M.-J., Lexer, M.J., 2011. Unraveling the drivers of intensifying forest disturbance regimes in Europe. Glob. Change Biol. 17 (9), 2842–2852. https://doi.org/10.1111/j.1365-2486.2011.02452.x.

Seidl, R., Schelhaas, M.-J., Rammer, W., Verkerk, P.J., 2014. Increasing forest disturbances in Europe and their impact on carbon storage. Nat. Clim. Change 4 (9), 806–810. https://doi.org/10.1038/nclimate2318.

Skogsdata 2023 (2023). *Skogsdata*. SLU Institutionen för skoglig resurshushållning.

Skogsstyrelsen (2021). Skogsskador i Sverige 2020. 57.

Skogsstyrelsen (2022). Skogsskador i Sverige 2021. 2022/06, 53.

Wermelinger, B., 2004. Ecology and management of the spruce bark beetle *Ips typographus*—a review of recent research. For. Ecol. Manag. 202 (1), 67–82. https://doi.org/10.1016/j.foreco.2004.07.018.

Zimová, S., Dobor, L., Hlásny, T., Rammer, W., Seidl, R., 2020. Reducing rotation age to address increasing disturbances in Central Europe: Potential and limitations. For. Ecol. Manag. 475, 118408 https://doi.org/10.1016/j.foreco.2020.118408.