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Abstract

In recent years, there has been a strong focus on how forests can mitigate climate change and sustainably provide ecosystem services. In this context, natural disturbances have gained importance, as severe disturbances may pose a threat to the provision of ecosystem services such as timber production. This thesis expands our understanding of how forest management planning can mitigate forest susceptibility to disturbance by investigating the connection between well-known management strategies and their influence on the forests' susceptibility to damage by major natural disturbances in Sweden. In addition, the thesis presents new forest planning models specifically addressing European spruce bark beetle insect and wind damage, given their importance in Sweden. The forest planning models developed in the research underlying this thesis use exact optimization methods to achieve specific spatial forest characteristics enhancing resistance to natural disturbances by identifying the optimal management for each stand in the landscape over the planning horizon. To reduce the forest's susceptibility to spruce bark beetle attacks, management strategies should prioritize shorter rotation periods and incorporate mixed-species stands. In contrast, to reduce forest susceptibility to wind damage, it is important to reduce the length of forest edges exposed to wind as well as avoid undertaking final harvests near mature stands to help in maintaining shelter between forest stands. The studies in this thesis reveal that adaptation costs can affect net present value and total harvest volumes by 5 to 10%, reducing substantially forest susceptibility. To conclude, the understanding of each type of disturbance is of the utmost importance for adapting forest management to either reduce or promote specific forest characteristics that affect susceptibility. This thesis shows that, with well-oriented forest management planning, there are good opportunities to reduce susceptibility to damage from natural disturbances.

Keywords: decision support system, ecosystem services, forest management, forest planning, forest susceptibility, linear programming, mixed-integer programming, natural disturbance, spruce bark beetle, wind damage.

Skoglig planering i syfte att minska skador relaterade till klimatförändringar

Sammanfattning

Under de senaste åren har skogen och dess möjligheter att mildra klimatförändringarna och hållbart tillhandahålla ekosystemtjänster fått mycket uppmärksamhet. Här har naturliga störningar en viktig roll eftersom dessa kan hota ekosystemtjänster som till exempel virkesproduktion. Denna avhandling ökar vår förståelse av hur skoglig planering kan minska skogens känslighet för störningar genom att genomlysa olika naturliga störningar i svenska skogar samt undersöka sambandet mellan vanliga skogsskötselstrategier och deras effekter på skogens känslighet för olika skador. Dessutom presenteras nya planeringsmodeller som specifikt behandlar skador av den europeiska granbarkborren och av vind, d.v.s. störningar som är aktuella i Sverige. Modellerna baseras på en optimerande ansats för att identifiera optimal skötsel som ökar motståndskraften mot naturliga störningar för varje bestånd och som ger upp till specifika rumsliga skogstillstånd på fastighetsnivå. För att minska känsligheten för granbarkborre bör skogen brukas med kortare omloppstider och med flera trädslag. För att minska känsligheten för vindskador bör man minska längden på av beståndskanter som exponeras för vind och undvika slutavverkningar intill bestånd som är känsliga för vindskador. Studierna visar även att anpassningar av skötseln för att minska skogens känslighet för att drabbas av skada kan påverka skogens ekonomi samt den totala avverkningsvolymen med 5 till 10 %. Förståelsen av varje typ av störning är avgörande för att anpassa skogsskötseln och minska känsligheten. Denna avhandling visar att avancerad och ändamålsenlig skoglig planering kan minska känsligheten för skador från naturliga störningar.

Nyckelord: beslutsstödsystem, blandad heltalsprogrammering, ekosystemtjänster, europeiska granbarkborren, linjär programmering, naturliga störningar, skogens känslighet, skoglig planering, skogsbruk, vindskador.

The only road that I need is the one that leads to trees.

Angie Weiland-Crosby

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. **López-Andújar Fustel, T**., Öhman, K., Klapwijk, M., Lämås, T., Björklund, N., Boberg, J., Cleary, M., Felton, A.M., Felton, A., Neumann, W., Nilsson, C., Olson, Å., Rönnberg, J., Eggers, J. Natural disturbances and the influence of management on forest susceptibility to damage: A literature review. (manuscript)

II. **López-Andújar Fustel, T**., Öhman, K., Klapwijk, M., Nordkvist, M., Sängstuvall, L., Lämås, T., Eggers, J. (2024). Impact of management strategies on forest susceptibility to spruce bark beetle damage and potential trade-offs with timber production and biodiversity. Forest Ecology and Management, 563, 121964. https://doi.org/10.1016/j.foreco.2024.121964.

III. **López-Andújar Fustel, T**., Öhman, K., Lämås, T., Eggers, J., Klapwijk, M., Rönnqvist, M. A spatial optimization approach to reduce forest susceptibility to spruce bark beetle outbreaks at the landscape level. (manuscript)

IV. **López-Andújar Fustel, T**., Eggers, J., Lämås, T., Öhman, K. (2021). Spatial optimization for reducing wind exposure of forest stands at the property level. Forest Ecology and Management, 502, 119649. https://doi.org/10.1016/j.foreco.2021.119649.

Papers II and IV are reproduced with the permission of the publisher.

The contribution of Teresa López-Andújar Fustel to the papers included in this thesis was as follows:

I. Developed the research idea together with the co-authors, performed large parts of the review reading, and wrote the manuscript with support from the co-authors.

II. Developed the research idea together with the co-authors, wrote the programming code in Heureka PlanWise, conducted the analyses, and wrote the manuscript with support from the co-authors.

III. Developed the research idea, conducted the analyses, and wrote the manuscript with support from the co-authors.

IV. Developed the research idea together with the co-authors, conducted the analyses, and wrote the manuscript with support from the co-authors.

Abbreviations

CCF	Continuous cover forestry
DSS	Decision support system
IP	Integer programming
LP	Linear programming
MIP	Mixed-integer programming
NFI	National forest inventory
NPV	Net present value
SBB	Spruce bark beetle

1. Introduction

Forests provide our society with numerous ecosystem services that contribute to improving our quality of life. In recent decades, demands on forests have increased for various reasons. For example, climate change and its numerous consequences have led to an increased pressure to manage our forests to compensate for CO_2 emissions through carbon fixation and the promotion of wood products to replace other materials. Climate change, together with the approach to managing the forest over many decades, has influenced the impact of natural disturbances on forest dynamics. A new focus on how to plan forest management to reduce damage to forest resources may be needed when the impact of natural disturbances is large, both in area and the time over which the forest is affected. The research described herein expands our understanding of how forest management can mitigate forest susceptibility to disturbance by reviewing a wide range of natural disturbances in Swedish forests. In addition, new forest planning models that take account of forest characteristics as well as species composition less prone to natural disturbance damage have been developed. Planning models encompass the definition of a problem to solve using mathematical terms, including goals and constraints built up on parameters and variables (further details in section 1.4.2). The models focus on wind damage and the European spruce bark beetle (*Ips typographus* L. (Coleoptera, Scolytidae)) (SBB), which are important natural disturbances in Sweden. In addition, the connection between common management strategies in forest management and their effects on the forest's susceptibility to damage from the most important natural disturbances in Sweden is investigated.

1.1 Forestry in Sweden

Sweden is one of the countries with the highest percentage of forest cover in the world. In total, 69% of its surface is covered by forest, which is equivalent to approximately 28 Mha, of which 23.5 Mha are considered productive forest (Skogsstyrelsen 2014; Nilsson et al. 2021). For many decades, the primary focus of Swedish forests has been wood production (Roberge et al. 2020) In this context, the tree species that have been most favoured due to their economic value - at the expense of other species – are Norway spruce (*Picea abies* H. Karst) and Scots pine (*Pinus sylvestris* L.). Currently, these two tree species, dominate 80% of Swedish forests, with Norway spruce accounting for 47% and Scots pine 33% (Nilsson et al. 2021). In the late 20th century, interest in promoting biodiversity began to increase and, other tree species such as birch (*Betula pendula* Roth. and *Betula pubescens* Ehrh.) and other deciduous trees species have increased their presence in forests (Roberge et al. 2020). In addition, approximately 6.1 % of productive forest land is formally protected at present (Statistics Sweden 2023). Due to the high interest in wood production, the most common type of forest management, which has been prevalent for many years and continues to be used today, is even-aged rotational forestry (Lundmark 2020). However, this type of management has led to many forest stands being dominated by just one tree species. In recent years, the impact of climate change and severe natural disturbance events have heightened interest in understanding how forest characteristics influence their susceptibility to damage by natural disturbances (Seidl et al. 2011). It has been observed that, in general, forests dominated by a single tree species are less resistant to the impacts of natural disturbances (Jactel et al. 2009; Felton et al. 2024). In Sweden, the forest industry plays an important role in supporting the economy, and internationally, is one of the largest exporter of pulp, sawn timber, and paper in the world (SFIF 2024). For this reason, there is a need for greater knowledge on how forest management planning can achieve the creation of resistant forests to damage by natural disturbances over time (Felton et al. 2024).

1.2 Climate change impacts on Swedish forests and natural disturbances

Current climate change projections indicate that future climate conditions will be more favourable for many natural disturbance agents, placing forest management and its potential to create resistant forests in the spotlight. Climate change is expected to have a large influence on the growth of boreal forests (Venäläinen et al. 2020). The need to adapt is particularly acute at high latitudes, where the largest increase in mean temperature is forecasted (Hoegh-Guldberg et al. 2018). Global warming may continue amplifying the changes in snow cover and frozen ground in Scandinavia in the future (Lemke et al. 2007). In addition, species and population shifts towards northern areas are likely to take place under a warmer climate. On the other hand, numerous studies point to an upward trend of natural disturbance damage in European forests since several decades (Seidl et al. 2014; Senf & Seidl 2021). Likewise, favourable conditions for the invasion of alien species will probably emerge (Taulavuori 2013). A recent study by the Swedish Forest Agency described several of the implications that this warming may have in the country indicating, for every 1°C increase, an approximate vegetation shift of 150 km north and 140 m upwards in elevation (Skogsstyrelsen 2019). In Sweden, temperature escalation is expected to influence the duration of the growing season and thus forest productivity, where cold temperatures and nitrogen levels are now a limiting factor for growth (Hellstrom et al. 2001; Majdi & Öhrvik 2004). However, forest disturbances will also be influenced by these changes.

Natural disturbances are part of the evolution and current state of forests (Pickett 1985; Johnstone et al. 2016). However, climate change and its influence on natural disturbances can increase the pressure over some ecosystem services and endanger their long-term provision (Thom & Seidl 2016). For example, there is evidence that climate change is expanding the area of forest that is prone to various disturbances, increasing the risk of damage (Lindner et al. 2010). In addition, climate change is also increasing the frequency and magnitude of some disturbances (Schelhaas et al. 2003; Gardiner et al. 2010). For example, the reproduction cycle of SBB is highly dependent on temperature, where higher temperatures can favour rapid population growths and larger survival rates (Wermelinger & Seifert 1999). Warmer weather conditions may favour the total number of generations that the SBB has in some locations. In Sweden, there are usually 1 or 2 generations per year depending on the location (Öhrn 2012). However, future warmer conditions and longer growing seasons could increase the number of generations if conditions are particularly favourable (Jakoby et al. 2019).

In addition to the above, the geographical distribution of disturbance agents where current temperatures act as a limiting factor for distribution ranges might expand in the future (Bale et al. 2002). Furthermore, the overall precipitation change is forecasted to be positive annually, however, the extent of dryer periods may increase during summer season (Kjellström et al. 2021). In addition, the recurrence of severe drought years may continue escalating according to current projections (MSB 2017). Higher average temperatures and severe drought can affect the vitality of the forest, weakening tree defences and making them much more susceptible to attack by SBB (Netherer et al. 2015).

1.3 Forest management

Forest management shapes and defines forest characteristics in a specific way to achieve objectives defined by forest owners, forest companies or society. Forest management encompasses a diverse set of silvicultural practices and commonly takes economic, ecological and social aspects into account (Wang 2004; Bettinger et al. 2016). Each silvicultural practice has specific consequences for the creation and development of certain forest characteristics and tree species composition. Depending on the objectives established by forest owners or society, different types of silvicultural practice will be chosen to achieve what is required from the forest.

Forest management is a subject of debate, being a widely discussed topic and recognized for its potential to contribute positively to the mitigation of climate change, environmental conservation, and its contribution to the development of the economy and social well-being (Siry et al. 2005; Baul et al. 2017; Kauppi et al. 2022; Ameray et al. 2023). Forests can positively contribute to climate change mitigation as carbon dioxide sinks and also through carbon storage in wood products, for example, furniture or construction materials (Gustavsson et al. 2017; Kauppi et al. 2022). Furthermore, forest management plays an important role in biodiversity conservation, to protect, preserve and restore the diversity of species in different ecosystems (Davis et al. 2001; Mauser 2021). Thanks to the various positive contributions that it is possible to obtain from forests, the interest in preventing future damage to forest resources caused by natural disturbances has increased in recent years. Natural disturbances are part of ecosystem processes, promoting the diversity of structures and altering the species composition of the place (Thom & Seidl 2016; Bowd et al. 2021; Shorohova et al. 2023). However, when extensive forest damage causes timber losses of millions of cubic metres, the negative impacts on natural resources and biodiversity become problematic, prompting the development of solutions to prevent future recurrence (Patacca et al. 2023).

In this context, over several decades, scientific studies have investigated why similar natural disturbances affect one forest area more than another, trying to link certain forest characteristics or species composition to greater susceptibility to damage from various disturbances (Bengtsson et al. 2000; Spittlehouse & Stewart 2004; Seidl et al. 2018; Zimová et al. 2020; Potterf et al. 2024). For example, wind damage and its relationship with stand characteristics have been studied in several European countries such as Sweden (Persson 1975), Denmark (Lohmander & Helles 1987), Ireland (Ní Dhubháin et al. 2009), and Germany (Albrecht et al. 2012). Forest characteristics and tree species compositions could be used to identify the forest's susceptibility to future wind damage. However, it must be noted that the fact that one forest is more prone than another to suffer damage from a natural disturbance does not necessarily mean that it will suffer more damage than the other the next time this natural disturbance affects these forests. This thesis focuses on forest susceptibility to natural disturbances, meaning the inherent predisposition or tendency for a forest to suffer damage. However, it does not address the risk of damage, which refers to the probability of a forest being damaged by such disturbances. It is important to highlight that the damage caused by natural disturbances does not depend solely on the characteristics of the forest but can also be influenced by the characteristics of the disturbance itself (e.g. wind speeds). In addition to the above, climate change can also influence the damage caused by a natural disturbance by, for example, increasing the exposure of the forest to disturbances or altering disturbance frequency (Dale et al. 2001). Following the example of wind damage, climate change can influence and reduce the length of the soil frost period during winter months due to warming. As a consequence, a shorter period of soil frost would increase the likelihood of wind damage during storms due to less anchorage of the roots to the soil (Gregow et al. 2011).

To conclude, there are many factors that influence the susceptibility of the forest to damage, and forest management is one of the most important. Furthermore, forest management is practically the only thing that can be controlled and used as a tool to create more resistant forests. The planning of forest management, spatially and temporally, requires the use of forest planning models to investigate management alternatives and set the overall management direction. In this thesis emphasis has been placed on a variety of management strategies, including various silvicultural practices, that influence the susceptibility of the forest to different natural disturbances, integrating them into the forest planning process to make the forest less prone to damage in the future.

1.4 Forest planning potential

Forest planning will determine where and when to implement specific silvicultural practices to achieve the objectives established for the forest to achieve good spatiotemporal coordination of silvicultural practices (Bettinger et al. 2016). Forest planning is of great importance as it sets the management direction to follow, based on a thorough understanding of current forest characteristics and how their development should progress over time to achieve desired characteristics and meet defined goals. The development of forests is slow, it can take many years to achieve certain objectives, and therefore the choice of silvicultural practices at any given time is especially important due to their long-term consequences (Hynynen et al. 2015). In this section, the importance of forest planning is discussed in depth.

Forest planning can be carried out at different dimensions, both spatial and temporal. Decision making at a spatial level is typically applied on three specific levels: tree level, stand level or landscape level (or property level) (Bettinger et al. 2016). The smallest scale is the tree level in which the actions taken affect individual trees belonging to a forest area. The stand level scale is applied to forest management units, stands, that contain a forest area with homogeneous or similar characteristics, growing in a location with fairly uniform site quality characteristics (Ståhl et al. 1994; Helms 1998). In practice, small variations between trees within a stand are common. However, from a management perspective, it is generally assumed that managing the entire stand area uniformly is more effective, given that its characteristics are largely consistent. Some of the characteristics used to delineate stands are tree species composition, age-class distribution, density, or dominant tree height (Helms 1998). In the forest planning process, the delineation of a stand is considered constant over time and does not change over the planning horizon analyses. The landscape or property level is the largest spatial scale and takes into consideration the complexity and interconnection of different stands, the management units, that make up the forest. This level of planning integrates the management of various forest areas within the landscape, considering the overall objectives for the entire landscape. It aims to apply the most suitable management strategy to each stand based on its specific characteristics (Morgan et al. 2021; França et al. 2022). Landscape level planning requires a different approach compared to the two other levels due to the increasing size and complexity of the problems at that level, including, for example, the spatial interconnections between the stands contained within it (Öhman 2001). These problems can grow up due to there being a large number of forest stands, as well as the numerous possible management alternatives than can exist for each stand. The landscape level scale is the one used for the work described in this thesis (Papers III and IV).

Apart from the three spatial scales presented, decision-making in forest planning also has a temporal scale (Bettinger et al. 2016). The time scales used can range from days or weeks to decades or hundreds of years. These scales follow a hierarchical approach and are divided into three main categories: operational, tactical, and strategic planning, representing short-, medium-, and long-term forest planning, respectively. The three scales are related to each other since the long-term objectives defined in strategic planning steer management planning at the tactical and operational scales (Cea & Jofré 2000). Operational planning addresses planning in the short-term, from days to several months. This planning involves detailed scheduling of activities such as which stands to harvest in the coming weeks, the location of landings for use during harvesting, or infrastructure maintenance. This level of planning is used to plan, in detail, the activities that are necessary to implement to achieve the established objectives of tactical planning. Tactical planning addresses the planning and execution of silvicultural practices to meet medium- and short-term goals i.e., goals up to 10 years ahead (Church et al. 2000). These plans usually include spatial information about where and when to perform certain silvicultural practices.

If spatial considerations are included at the tactical level but are neglected at the strategic level, the result may be a failure to achieve the objectives specified in the strategic plan. Strategic planning involves the definition of long-term objectives, as well as the development of strategies that can potentially be used to deliver them (Sessions & Bettinger 2001). In this phase, for example, the trade-offs between different ecosystem services over time or the balance between resources that can be obtained in the short-term versus those that can only be obtained in the long-term can be analysed. Decisions are also made in relation to the total volume to be harvested, the forest characteristics and species composition to be achieved, or the spatial characteristics to be created in the landscape over time. Typically, strategic planning uses planning horizons equivalent to at least one rotation period (if even-aged forestry is being undertaken). The research underlying this thesis made use of this planning scale, and the planning horizon used was 70 years, which approximately represents the average rotation period for the forest areas studied.

The forest management plans obtained from the three levels of spatial and temporal planning are periodically updated to adjust the planned activities to small or large changes in forest conditions that occur throughout the life of a forest. The periodic update of plans is very important since forest development can be altered by many factors beyond our control, such as natural disturbances, or the need for the forest owner to advance or delay harvesting for various reasons.

1.4.1 Forest simulations

Forest planning commonly explores and evaluates a large number of forest development possibilities and management alternatives for a forest property, identifying the most appropriate one according to the objectives set. To explore a relevant subset of management possibilities, it is necessary to model and simulate forest development for all stands belonging to the forest area under study.

In the field of forest planning, carrying out simulations is very interesting since it allows projections to be made and shows the direction of development of the forest under different management strategies (Muys et al. 2010). Planning also allows the study and evaluation of possible consequences of climate change on forest development, investigating trade-offs between different variables, and the study of directions of change in forest development due to different causes (Bettinger et al. 2016).

In this thesis, forest simulations with the general objective of changing and creating new forest characteristics that contribute to making the forest less susceptible to damage by different abiotic and biotic agents such as wind or SBB have been utilized. The simulations also allowed the study, in an approximate manner, of how much time is necessary to generate new forest characteristics, as well as the consequences of these changes on other parameters such as harvest volume or financial outcomes, which are important for forest owners and companies whose main activity is timber production.

To be able to choose the best possible combination of treatment programmes for each stand in the forest, it is necessary to generate a sufficiently high number of simulations for each forest area. In this way, a relevant subset of possible management alternatives and outcomes can be explored, testing one type of management or another for the different stands, and proceeding to choose the most appropriate treatment programme for each stand to meet the landscape or property level objectives. A treatment programme is a sequence of silvicultural practices scheduled for a given stand to be implemented throughout the rotation period (further details in section 2.2). This last step is often carried out by applying operations research methods, explained in the following section.

1.4.2 Operations research

Operations research is a field that uses mathematics and modelling to find solutions to complex problems and thus support decision making (Churchman et al. 1957; Henningsson et al. 2010; Taha 2011). Optimization aims to find the best possible solution to a given problem within a set of possible solutions. In the forestry context, the decision problems that may be encountered usually have a very large number of possible solutions (Kangas et al. 2015). For example, a forest property with 10 stands may – due to its combinatorial nature – have millions of management options depending on the number of alternatives that exist for each stand. In other words, the set of possible solutions is equal to the number of possible alternatives for each stand raised to the power of the total number of stands. In this example, if for each stand there are five management alternatives, it would be calculated as 5^{10}, which is equal to 9,765,625 million possible management alternatives.

Thus, what at first may seem like a simple or small problem becomes a complex problem due to the large number of possible alternatives that the forest manager can decide to implement. In these cases, finding the best combination of all possible alternatives for each stand along the planning horizon can be very tedious, making the use of a computer essential (Borges et al. 2014).

The construction of optimization models is very important since their parameters and variables represent the characteristics of the real problem. Taha (2011) points out five main phases in the formulation and solution of optimization models, as follows:

- Description of the problem: detailed description of how the real problem is going to be simplified, as well as the associated limitations of the model inherent to its mathematical formulation. The objective of the model, the restrictions that must be met, as well as the decision variables will be defined.
- Construction of the optimization model: in this phase the description of the problem is translated into mathematical language. Normally, real problems are simplified mathematically to be able to address them.
- Model solution: different algorithms can be used to solve the model depending on the type of optimization model formulated. In this step, the model solution is also verified, whether it makes sense or not, as well as performing sensitivity analysis to study in detail how the model behaves with variations in the value of some parameters.
- Model validation: determine whether the proposed model adequately predicts the elements that are part of the model. In many cases, the model results are compared with historical data to verify that the model is working properly.
- Implementation of the solution: execution of the results obtained in practice.

In operations research, there are two main types of optimization method: exact methods and heuristic methods. Exact methods are composed of algorithms that guarantee to find an optimal solution to a problem given that such a solution exists. Within the exact methods, some of the most widely used mathematical models to represent a problem are linear programming (LP) (Dantzig 1951) and integer programming (IP) (including mixed-integer programming (MIP)) (Wolsey 2020). The most efficient algorithms that are used to find an optimal solution to these two types of model are the simplex method for LP and the branch and bound method for MIP. The search for the optimal solution can come at a large computational cost that can increase enormously with the size of the problem.

If the problems posed are very complex and the computational cost is excessive, heuristic methods can be used (Bettinger et al. 2002). These methods do not guarantee finding an optimal solution, nor do they provide a measure of the deviation between this solution and the optimal one, however, they can provide a reasonably good solution to the problem in question. Many of the heuristic methods are inspired by natural processes to guide the search for appropriate solutions (Yang 2010). Some examples of heuristic methods applied to the forestry field are tabu search, simulated annealing, and genetic algorithms.

In this thesis, the application of exact methods with LP (Paper II) and MIP models (Papers III-IV) is explored. More details about the methods used can be found in section 2.4. All the models have been constructed using a Model 1 formulation (Johnson & Scheurman 1977). Model 1 allows the inclusion of spatial aspects connected to each individual stand in the calculations over the planning horizon selected. With this type of formulation, treatment programmes spanning the planning horizon are generated for each stand. In comparison, Model 2 formulation aggregates those stands sharing similar stand characteristics such as age or vegetation into different strata (Johnson & Scheurman 1977). Model 2 therefore deals with a lower number of decision variables connected to each of the strata, which was important a few years back when less computational power was available to solve these problems. Therefore, the Model 1 formulation is used much more today than that of Model 2 since the increase in the number of decision variables does not represent as great a problem, in computational terms, as it did earlier (McDill et al. 2016; Martin et al. 2017).

1.4.3 Decision support systems (DSSs)

The complexity of forestry problems makes it difficult to deal with large amounts of data, to organize it, access it, and to analyse it. Managing this data to simulate different forest development scenarios can be complex. However, optimizing resource allocation and selection of forestry practices on a forest property can be an arduous task due to the high number of management alternatives that may exist for each of the stands. For these reasons, in the forestry field, it is common to run forest simulations and perform optimizations using DSSs (Nordström et al. 2019) that include growth and yield models. DSSs are made up of models that explore the relationships between different forest characteristics and allow the development of forest parameters such as growth in height or stem diameter at breast height to be simulated over time. DSSs help manage large amounts of data as well as their subsequent analysis, improve the efficiency of forest planning, promote forest sustainable practices, and assist in decision making. In summary, DSSs "*integrate database management systems with analytical and operational research models to solve ill-structured decision problems*" (Vacik et al. 2015).

There are three main types of DSS that can be classified based on the methodology they utilize, as well as the questions that can be answered with them, 1) simulation-based DSS, 2) optimization-based DSS, and 3) multi-criteria decision analysis DSS (Segura et al. 2014). Simulation DSSs are based on a set of models that represent forest growth and interactions between forest components. These DSSs, which answer "what if" questions, are intended to predict how forest stands can respond to different forms of management, different types of climate, etc. The output of this type of DSS is the generation of different future scenarios by rerunning the system given different management options for the selected stands. Optimization DSSs work by following two fundamental steps. The first step is the generation of a set of possible management options (treatment programmes) for each individual stand based on the same type of certain mathematical models as the DSS simulations. In the second step, considering the objective function, the constraints and the decision variables defined by the user, the system implements optimization algorithms to identify the best combination of treatment programmes at the forest level, maximizing or minimizing the established objectives. These DSSs answer the "how to" question by identifying the best possible management alternative for each stand to meet the forest level objectives. Finally, multi-criteria decision analysis DSSs help evaluate and select between alternatives or courses of action that involve multiple conflicting objectives and where there is no single optimal solution (Nilsson et al. 2016; Eggers 2017). This last type of DSS facilitates the participation of stakeholders in the analyses considering different preferences. In this thesis, Papers II and IV focus on the use of simulations and optimizations in the Heureka DSS to identify the optimal form of management in order to achieve the specified objectives in each of the papers (Lämås et al. 2023). In Paper III, Heureka DSS was used to simulate forest development and the AMPL software to find an optimal solution to the problem posed.

Optimization DSSs, like Heureka, can be used in practice to temporally organize management activities as well as spatially orient them in a specific way to reduce the effects of climate change or the damage caused by natural disturbances to the forest (Lämås et al. 2023). However, to make this possible, planning models taking these types of aspect into account are needed. Planning models help direct management to achieve certain forest characteristics over time to, for example, reduce the forest susceptibility to damage of some type. These types of planning model were developed in the research described herein, taking into account natural disturbances such as wind damage and SBB.

1.5 Objectives

This thesis has two main objectives: 1) to identify how forest characteristics and tree species composition influence susceptibility to damage and assess the effectiveness of adaptation strategies in forest management in reducing forest susceptibility to disturbance agents, and 2) to develop forest planning models to be used in DSSs with the objective of reducing the various negative effects that natural disturbances can have on production forests. This thesis contains a literature review to identify how the most commonly used adaptation strategies in forest management influence the susceptibility of the forest to the most important natural disturbances in Sweden by promoting changes in forest characteristics and species composition. In connection with the second objective of the thesis, the output of the developed planning models is the best possible combination of management at the forest level to generate forest characteristics and species composition resistant to natural disturbances. The forest characteristics and species composition that should be promoted to reduce the general susceptibility of any forest will be specific to each of the targeted natural disturbances considered in this thesis. Specific indicators or indices to evaluate the forest situation before and after executing the model optimization are used. These models are intended to be used in forest owner and company holdings. The optimization models are formulated using exact methods and can be implemented in many DSSs.

The individual objectives of each paper are as follows:

Paper I. The objectives of Paper I were 1) to identify how forest characteristics influence forest susceptibility to damage by major natural disturbances in Sweden, and 2) to identify opportunities, synergies and trade-offs for combining adaptation strategies in forest management to tackle several disturbances at once.

Paper II. The objectives of Paper II were 1) to assess the impacts of management strategies on forest susceptibility to SBB attack, and 2) to explore the potential to combine management strategies in different proportions to reduce overall forest susceptibility to attack by SBB. In addition, the impact on timber production and biodiversity of applying these strategies was evaluated.

Paper III. The objective of Paper III was to develop a forest planning model to achieve a forest landscape configuration with specific characteristics contributing to reducing the growth of SBB populations during outbreak phases while achieving the largest possible financial value over the planning horizon.

Paper IV. The objective of Paper IV was to develop a forest planning model to minimize the length of forest edges in Norway spruce stands to reduce forest susceptibility to wind damage over the planning horizon. In addition, the trade-off between economic outcomes and the perimeter of forest edges in the landscape was analysed.

2. Materials and methods

This chapter provides an overview of the diverse methods employed in the thesis, ranging from a literature review to simulation and optimization studies. It also details the geographical areas and datasets used in each study, ranging from a comprehensive review covering all of Sweden and beyond, to various specific case study areas within Sweden. The mathematical models implemented and their respective objective functions are also discussed.

Paper I employed a systematic literature review. The literature search was carried out in the Web of Science database collection and SCOPUS, the subsequent filtering of literature, by title and abstract, was performed in Rayyan (rayyan.ai), and finally the extraction of the necessary information from each article followed a protocol developed in Excel. Paper II simulated and optimized the forest development that would be obtained for various management strategies during an established planning horizon using the DSS Heureka PlanWise. The optimization was formulated as a LP model. Papers III and IV developed two new optimization models to consider relevant spatial characteristics to reduce forest susceptibility to SBB and wind damage at the landscape level. The problems raised were formulated as MIP models.

2.1 Systematic literature review (Paper I)

The review identifies synergies and trade-offs between adaptation strategies in forest management and their impacts on forest characteristics. It synthesizes quantitative evidence from the literature to understand and analyse the relationships between forest characteristics and species composition, along with forest susceptibility to major natural disturbances in Sweden.

The method chosen for the literature review was systematic, rigorous and focused on an exhaustive search of the literature as well as subsequent selection of literature and synthesis of information. In this study, a total of 13 researchers and an advisor from the Swedish Forest Agency were involved. Seven of the researchers were divided into four main groups targeting the most important natural disturbances in Sweden (description below). The rest of the people involved in the review provided supervision and guidance on the review design and manuscript writing. The disturbance groups were as follows:

1) Weather-related disturbance damage. In this group, wind and snow damage were reviewed.
2) Insect disturbance damage. In this group, damage caused by the European spruce bark beetle *Ips typographus* ((L.) (Coleoptera: Curculionidae, Scolytinae)), the European pine sawfly *Neodiprion sertifer* ((Geoffr.) (Hymenoptera, Diprionidae)), and the pine weevil *Hylobius abietis* ((L.) (Coleoptera, Curculionidae)) was reviewed.
3) Pathogen disturbance damage. In this group, two species of the root rot pathogen *Heterobasidion* spp. were included, *Heterobasidion annosum* sensu lato (Fr.) Bref. and *Heterobasidion parviporum* Niemelä & Korhonen. In addition, the root rot fungus *Armillaria* spp., and the Scots pine blister rust *Cronartium* spp. were included.
4) Browsing damage. In this group, the focus was on ungulate herbivore damage.

At the beginning of the study, a daylong online workshop was organized to gather all participants’ expertise, define the review objectives, and decide what adaptation strategies and major natural disturbances would be included in the review.

In the workshop, participants were asked to provide suggestions about the most important natural disturbances within each disturbance group for Sweden. In addition, they were also asked to discuss prospective adaptation strategies with high potential for reducing the forest's susceptibility to damage from each of the suggested disturbances. The major disturbance agents, both abiotic and biotic, that were selected to be included as part of one of the four disturbance groups are described above. The adaptation strategies to be included in the review were chosen after the workshop from a long list of management possibilities presented by the disturbance experts. The strategies selected are applicable at stand level, can potentially influence forest susceptibility to several disturbances, and are widely known in Sweden. The adaptation strategies selected are described in Table 1.

Table 1. Description of the adaptation strategies used in Paper I.

Adaptation strategy	Description
Baseline (business as usual)	• planting monocultures of Scots pine or Norway spruce, • performing a precommercial thinning, • two to three thinnings, and • final felling at the most economically advantageous rotation time.
Mixed-species stands	Same as baseline but: • a maximum of 70% of basal area is allowed for the dominant species, and • natural regeneration is allowed.
Shorter rotation period	Same as baseline but: • final felling is done before the most economically advantageous age is reached.
Longer rotation period	Same as baseline but: • final felling is done after the most economically advantageous age is reached.
Few or no thinnings	Same as baseline but: • at most only one thinning is performed during the rotation period.
Logging residue removal	Same as baseline but: • logging residues (tree tops and branches) from thinnings and final fellings are removed from the forest, and • tree stump removal (or tree stump treatment) in connection to root rot due its special relevance to this disturbance.
Prescribed burning	Same as baseline but: • performing prescribed burns to favour the presence of alternative species in the understory, and

	• prescribed burning can also be applied for site preparation after final felling.
Uneven-aged forestry	• selection felling involves the harvesting of trees of different ages and sizes to generate an uneven-aged structure (an approximate inverted J-shaped stem diameter distribution) in a forest stand over time. • patch cutting involves the harvesting of a forest area of at most 0.25 ha to maintain a continuous cover over time and generate an uneven-aged structure in the forest.

Before starting the literature search, two types of forest stand were defined in which to examine the influence of the selected adaptation strategies and susceptibility to damage from the selected major natural disturbances. The two types of forest stand chosen were Norway spruce-dominated stands and Scots pine-dominated stands. These types of forest are very common in Sweden and therefore of great interest to improve our understanding of how management could reduce damage to them.

The search strings were created and developed after framing the literature search to specific geographic areas, forest species, adaptation strategies and disturbance agents relevant in the context of forestry in Sweden. In total, three strings in each search were developed and used:

1) First search string: geography and tree species. Specific terms to capture literature connected to the two main types of forest stand in Sweden as well as literature relevant to boreal and temperate forests in Fennoscandia.
2) Second search string: adaptation strategies. Specific terms connected to each of the adaptation strategies included in the review.
3) Third search string: disturbance agents. Specific term selection targeting each of the disturbance agents included in the review.

The first search string was common to all searches and the terminology of search strings 2 and 3 was updated depending on the adaptation strategy and the disturbance agent addressed, as detailed below in an example of a search: search string 1 + search string 2 corresponding to the adaptation strategy “mixed-species stands” + search string 3 corresponding to the disturbance agent “browsing damage”. The three strings were as follows: 1) Geographic area and forest species. This first search string focused on the geographic area of northern Europe, in addition to adding some extra terms to cover the literature related to the boreal and temperate zones. This search string also included the names of the most economically important forest species in Sweden, Norway spruce and Scots pine. 2) Forest adaptation strategy. Specific terminology was included for each of the chosen adaptation strategies: mixed-species stands, shorter rotation times, longer rotation times, few or no thinnings, logging residue removal, prescribed burning and uneven-aged forestry. 3) Disturbance agent. Specific terminology corresponding to the following disturbance agents was used: wind and snow damage, the SBB, the European pine sawfly, pine weevil, root rot (*Heterobasidion* spp. and *Armillaria* spp.), Scots pine blister rust, and browsing damage.

The literature search was undertaken in a systematic and exhaustive way, in two databases – Web of Science and SCOPUS. The literature found in these two databases was mainly in the form of scientific articles, and some reports. In addition, the authors, experts in different areas, were allowed to include literature that was considered relevant to this study even if it was not initially found through the searches.

The literature was screened in two steps: first by title and abstract, and then by the content of the article. The Rayyan.ai website was used for the first initial screening of the articles. In addition, a protocol was developed specifying the precise information to be extracted from the literature to achieve the objectives of the review. Secondly, the article or report was read in its entirety to confirm whether it should be included or not. If the literature read provided information relevant to the objectives of the study, it was included. In addition, it was specified that the literature included had to be published after the year 2000 and be written in English.

The results were presented in an organized manner. First, the forest characteristics that make forests susceptible to damage were presented. Second, adaptation strategies and their potential to influence these identified forest characteristics were presented. Finally, in the discussion, the results were interpreted in the context of the study objectives.

2.2 Heureka PlanWise (Papers II–IV)

Papers II–IV made use of the Heureka forest DSS to simulate forest development for the selected planning horizons and the inbuilt optimization module aimed at finding the best possible combination of treatment programmes for the forest area included in the analyses (Papers II and IV). The optimization analysis in Paper III was performed using the AMPL software.

The Swedish Heureka forest DSS (Lämås et al. 2023) encompasses four pieces of software that serve to pose and solve different types of forest planning problem and at different geographical scales from individual stands to landscapes. Heureka PlanWise – one of the four pieces of software – has two main modules: 1) the simulation of forest development over a time period selected by the user and based on certain forest management specifications also defined by the user, and 2) an optimization module capable of solving LP and MIP models.

The Heureka PlanWise software was used to carry out the simulations in Papers II–IV, and the subsequent optimization of Papers II and IV, at county and landscape level, respectively. In this software it is possible to choose from three different management systems for the simulation of forestry development: even-aged forestry, continuous cover forestry (CCF) and no management. Within each of these alternatives it is possible to modify the Heureka silvicultural practice settings that influence the treatments. The software contains a set of models, fundamentally empirical, based on plot and tree level and yield models which the software relies upon to carry out simulations of forest development during the chosen planning horizon.

Heureka PlanWise uses the concept of “treatment programme” to define the forestry management that can potentially be used on a treatment unit – typically a stand or sample plot – during the planning horizon. The planning horizon is chosen by the user and Heureka performs the simulations in time-steps of 5 years, equivalent to one planning period in the programme. In Papers II–IV, the planning horizon chosen was 70 years, representing a normal rotation period for the study areas. Each treatment unit represents a forest stand (Papers III and IV) or a forest plot (Paper II). In this way, for each stand or plot, the software generates a set of potential treatment programmes that simulate forest development during a specified period of time and based on the settings selected for the chosen management system. For example, you can modify the settings that Heureka has by default for regeneration (soil preparation, the time to regenerate after final felling, tree species to plant etc.), the pre-commercial thinnings (e.g. height range over which the pre-commercial thinning is applied), or commercial thinnings (maximum and minimum percentage of basal area that can be removed etc.), among many management options.

Following the generation of treatment programmes, in the optimization module, the mathematical model that identifies the key aspects of the problem posed is defined along with the maximization or minimization objective function, subject to certain restrictions that must be met. The optimization will choose which treatment programme should be applied to each planning unit (stand or plot) to achieve the objective and respect the restrictions. The mathematical models allowed in the Heureka PlanWise optimization module must be formulated as LP or MIP models. Paper II used a LP model and Papers III and IV a MIP model. The models were formulated according to Johnson and Scheurman's (1977) Model 1 formulation. The decision variables of Model 1 represent the assignment of a treatment programme to each stand, the treatment programme representing the sequence and timing of the silvicultural practices that will be carried out during the planning horizon.

2.3 Evaluation of forest management strategies using National Forest Inventory data (Paper II)

Paper II investigates the potential of five different management strategies to reduce forest susceptibility to SBB attack. In this study, national forest inventory (NFI) plots representing the forest characteristics, both vegetation and site variables, of Kronoberg county in southern Sweden during the period 2016–2020 were used. The Swedish NFI plots are composed of data from temporary and permanent sample plot measurements and are distributed throughout the country, covering different climatic gradients and types of management. The plots are circular, and their area varies depending on whether they are permanent (314 m^2) or temporary (154 m^2) (Fridman et al. 2014).

In Paper II, only NFI sample plots with Norway spruce as the dominant species were included in the analyses, i.e. NFI plots with over 70% of their basal area dominated by Norway spruce. In total, 680 NFI plots were included in this study, representing a forest area of 368,041 hectares. For the selection of management strategies and the subsequent simulation of forest development for each strategy in each plot, a reference strategy was first established representing business-as-usual (REF). The reference strategy comprised planting with a single tree species, pre-commercial thinning, two or three commercial thinnings and final felling at the most advantageous economic time. The other management strategies were mixed-species stands (MIX), short rotation without thinnings (SHORT), long rotation (LONG) and continuous cover forestry (CCF) (description in Table 2).

Forest development for the different management strategies was simulated in the DSS Heureka PlanWise. Subsequent optimization was also carried out supported by a LP model in Heureka PlanWise. In addition to the previous forest management strategies, a combined strategy (ALL), was studied in which all the strategies were available to be chosen by the Heureka PlanWise optimization routine. In this combined strategy, an optimal combination of management strategies was investigated, as well as the proportion in which each strategy would be used to achieve the objective and respect the restrictions of the proposed mathematical model (see Paper II). The settings for each forest management strategy plus the combined strategy represent different ways or approaches to target specific forest characteristics that are important from a SBB susceptibility perspective. In addition, a biodiversity evaluation of the use of these management strategies based on three indicators suggested in the Swedish environmental goals Living forests consisting of old forest (area of productive forest with a mean age over 120 years), mature broadleaf-rich forest (productive forest area with at least 25% broadleaved tree species), and forest area with large trees (at least 60 trees per hectare with minimum stem diameters of 45 cm for conifers and 35 cm for broadleaves) is included (Andersson et al. 2022).

The quantification of forest susceptibility to SBB uses an index developed by Nordkvist et al. (2023). This index is based on what are considered the most important forest parameters influencing the chances of SBB infestations. Each parameter of the index contributes to the total value of the index to a varying amount, depending on both the value of the parameter and its level of contribution. The level of contribution to the index depends on the scientific evidence that exists for that parameter; those parameters for which there is strong empirical data indicating their relationship with SBB infestations (e.g. Norway spruce volume) will contribute more to the value of the index than parameters for which there is not much empirical data (e.g. birch volume).

Table 2. Description of management strategies used in Paper II.

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 (PCT) when trees are between 2 to 6 meters high to remove tree species other than Norway spruce, • thinnings, up to two or three times during the rotation period, and avoided when trees are +20 m high, • retention of 10 trees/ha and three high stumps/ha after final felling, • set aside 10% of forest area at final felling, and • as an exception, after final felling in dry soil types, Scots pine seedlings planted instead of Norway spruce.
Mixed-species 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 planted irrespective 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-diameter trees of Norway spruce.	Same as REF but: • no thinnings allowed, • minimum final felling age reduced by 10% and, • a maximum delay on the execution of the final felling 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 set to 50 years.
Continuous cover forestry (CCF)	Increase local tree size diversity and favour a wide range of forest structures.	In this strategy, no final fellings performed and the removal of timber from the forest carried out by a series of selection fellings, implemented as thinnings from above.

2.4 Spatial optimization in forest planning using mixed-integer programming formulations to address wind and insect disturbances (Papers III and IV)

Papers III and IV present two different MIP models to consider from a spatial perspective. Paper III focuses on the distribution of highly susceptible forest zones in the landscape to SBB attacks and Paper IV focuses on edge effects related to wind disturbance at the landscape level.

Paper III

In Paper III, a MIP model with four main components in the objective function and subject to certain restrictions was developed. The four main components were divided into two terms in the objective function, the first term for objective 1, and the second term for objectives 2, 3, and 4 (see the explanation below). These two terms were weighted according to the parameter α which determines the weight given to each part of the equation. The higher the value of α the greater weight is given in the model to the first term corresponding to the economic outcome. In contrast, the lower the value of α the greater weight is given to the second term, corresponding to the SBB forest susceptibility components. In addition, three individual weights were added to each of the susceptibility components, e_1, e_2, and e_3, to perform a subsequent sensitivity analysis to assess how different input weights for each component would impact the variability of model outputs.

The four main components of the objective function were 1) the economic outcome, based on the net present value (NPV), 2) the forest landscape susceptibility to damage by SBB (average SBB susceptibility index for the whole landscape), 3) total distance between SBB highly susceptible zones, and 4) total size of the SBB highly susceptible zones in the forest landscape. Objectives 2, 3, and 4 targeted three different aspects to reduce SBB susceptibility in the forest landscape. Objective 2 represented the total average of the SBB susceptibility index for the entire landscape and for the given planning horizon of 70 years. The average of the SBB index indicated differences in relative susceptibility of stands in the same forest landscape. Objectives 3 and 4, targeted spatial characteristics known to have an influence on the forest susceptibility to SBB at the landscape level. Objective 3 maximized the total distance between SBB highly susceptible zones, and objective 4 minimized the size of those highly susceptible zones.

Objective function terms and objectives are presented below. The objective function minimizes the sum of both terms.

Minimize z = *Term 1* + *Term 2*

Term 1
Objective 1: economic outcome (NPV)

$$\alpha * \sum_{i \in I} \sum_{s \in S} -n_{is} a_i x_{is}$$

Term 2
Objectives 2 + 3 + 4: SBB forest susceptibility components

$$(1 - \alpha) \; * \; (\, e_1 \sum_{i \in I} \sum_{s \in S} \sum_{t \in T} p_{ist} a_i x_{is}$$

$$+ e_2 \sum_{i \in I} \sum_{j \in J : j \neq i} \sum_{t \in T} \frac{1}{(1 + d_{ij})} \left(\frac{a_i + a_j}{2} \right) u_{ijt}$$

$$+ e_3 \sum_{i} \sum_{k \in K} \sum_{t \in T} (f_k y_{ikt} + c_k q_{ikt}))$$

where,
a_i is the area of stand *i*,
d_{ij} is the distance between stand *i* and stand *j*,
n_{is} is the total NPV of stand *i* using treatment programme *s*,
p_{ist} is the SBB forest susceptibility index for stand *i* using treatment programme *s* and for time period *t*,
f_k is the penalty cost of highly susceptible forest area of size *k*, (different area sizes of highly susceptible forest, *k*, have different penalty costs),
c_k is the penalty cost of continuous area sizes of highly susceptible forest of size *k*, (different continuous areas sizes of highly susceptible forest, *k*, have different penalty costs),
q_{ikt} is the total area allocated to a seed zone *i* for size *k* in period *t*,
e_1, e_2, e_3 are the individual weightings of the three components connected to the forest susceptibility to SBB to the value of the objective function,
x_{is} takes the value of 1 if stand *i* uses treatment programme *s*, 0 otherwise,

u_{ijt} takes the value of 1 if stand i and stand j are both above the index threshold L in period t, 0 otherwise, and
y_{ikt} takes the value of 1 if stand i is a seed zone for a "highly susceptible" area of size k in period t, 0 otherwise.

An even-flow harvest constraint to limit the maximum difference in harvest volume, to ±20% between two consecutive periods over the planning horizon was included. Also included in the model were constraints to identify those stands that have a high susceptibility to SBB attacks, as well as constraints to create the high susceptibility zones, composed of one or several stands that had high susceptibility and share a common border.

The model was tested on four different study areas of different sizes but with similar forest characteristics. These study areas are located at the Asa forest property, belonging to the state-owned forest company Sveaskog, in southern Sweden and are largely dominated by Norway spruce (Table 3).

Table 3. General description of the four study areas. Data on Norway spruce average age, volume per hectare, and volume proportion are given for Norway spruce tree species. *the data provided correspond to the initial forest condition at year 0 of the simulation.

Study area	Number of stands	Study area size (ha)	Average age (years)*	Volume (m^3/ha)*	Volume proportion (%)*
I	56	173	38	202	85
II	114	353	42	223	87
III	204	577	44	232	86
IV	290	781	45	224	85

The simulation of forest development was conducted in Heureka PlanWise and the mathematical model was run in AMPL and solved with CPLEX selecting a MIP gap of 0.00001. The mathematical model was run for two extreme values of α; α=1.00 and α=0.00. Setting α=1.00 corresponds to maximizing the first term without considering the components of forest susceptibility to SBB, whilst α=0.00, corresponds to minimizing the second term without considering the economic outcomes. In addition, the three individual weightings, e_1, e_2, and e_3, were tested individually and for three times more than the weight set in the prior optimizations.

Paper IV

In Paper IV, a MIP model to reduce forest susceptibility to wind damage by targeting the total length of Norway spruce-dominated forest edges with large height differences between two adjacent stands was developed. The objective function minimizes the sum of the total length of the forest edge perimeter with a minimum selected height difference, represented by parameter *d*, between two adjacent stands. The parameter *d* is selected by the user and is included in the constraints of the model. Three different *d* cases with different minimum height differences to identify forest edges were used; *d* set to 5, 10, and 15 meters respectively. That is, i.e. for case *d* = 5, if the height difference between two adjacent stands is more than 5 meters, the Norway spruce forest edge would be considered exposed to damage by wind. Furthermore, the model was subject to an even-flow harvest demand that guaranteed a maximum harvest volume difference between consecutive periods of 20%. In addition, the model is also subject to a minimum NPV percentage demand. The model was solved nine times for each NPV demand (70, 80, 90, 95, 96, 97, 98, 99, and 100%) and three times for each value of *d* (5, 10, and 15 meters). In total, the model was solved 27 times (9 NPV demands * 3 *d* values). To calculate the maximum possible NPV that could be obtained with the model, first the model for each *d* value was solved with a demand of 100% NPV without considering minimization of exposed forest edges at the property level.

The study area selected to test the model is located in southern Sweden and has a similar proportion of Scots pine (48%) and Norway spruce (45%). Forest development simulation and optimization were performed using Heureka PlanWise with the Gurobi 8.0 solver. The objective function is described below:

$$Minimize\ Y = \sum_{i \in I} \sum_{l \in L_i} b_{il} \sum_{p \in P} Z_{ilp}$$

where,

I is the set of stands,

L_i is the set of neighbouring stands to stand *i*,

P is the set of time periods,

b_{il} is the common edge length between stands *i* and *l*,

and decision variable,

Z_{ilp} takes the value of 1 if the common edge between i and l is considered an exposed forest edge, 0 otherwise.

3. Summary of each paper

In this chapter, a brief general description of the purpose of each study is presented at the beginning of each section, followed by a summary of the main results and a discussion of that paper.

3.1 Connections between adaptation strategies in forest management and forest susceptibility to major disturbances in Sweden (Paper I)

Paper I focuses on understanding the forest characteristics and species composition that influence the susceptibility of the forest to damage from the major disturbance agents in Sweden. Furthermore, this study also identifies synergies and trade-offs between commonly used adaptation strategies and their impact on forest susceptibility to damage caused by the major natural disturbances included in the literature review.

The results from Paper I show that the forest characteristics and species composition upon which each natural disturbance depends are specific and different compared to the other disturbances. For example, within the group of insects, the SBB and the European pine sawfly are specialized on different species, Norway spruce and Scots pine respectively. However, pine weevil can affect a broader range of forest species including Norway spruce and Scots pine (Wallertz 2009). Something similar is observed in the pathogen group, where *Heterobasidion annosum* affects a wide range of tree species while *Heterobasidion parviporum* is, in general, specific to Norway spruce, and *Chronartium flaccidum* to Scots pine in Northern Europe (Samils & Stenlid 2022). Browsing damage by ungulates is also strongly related to tree and shrub species and their availability in the landscape (Nevalainen et al. 2016). Ungulates have a very strong preference for oak (*Quercus robur*), aspen (*Populus tremula*), willow (*Salix caprea*), rowan (*Sorbus aucuparia*), and bilberry (*Vaccinium myrtillus*) (Månsson et al. 2007; Felton et al. 2022b). In the absence of these species, browsing damage can be concentrated on other forest tree species such as birch or Scots pine. On the other hand, weather-related disturbances can also be related to specific tree species that have certain structures or shapes that make them more susceptible to wind and snow damage. For example, tree species with dense canopies during the winter, such as conifers, are more likely to suffer damage from snow accumulation compared to other tree species that shed their leaves in autumn and do not favour the accumulation of snow on their branches (Hedstrom & Pomeroy 1998; Päätalo et al. 1999).

When it comes to biotic agents, in addition to their direct relationship with specific tree species, other forest characteristics must also be present for these agents to utilize the resources. For insects, the SBB needs mature forests of Norway spruce, preferably composed of trees with large stem diameters with sufficient bark thickness to bore galleries in the tree bark and deposit eggs. When the larvae emerge, they will feed in phloem of the trees (Holsten et al. 1999; Göthlin et al. 2000). The European pine sawfly prefers monocultures of Scots pine and low structural diversity in forest stands to avoid potential predator pressure (Nordlander 1987; Kaitaniemi et al. 2007; Bellone et al. 2017). The pine weevil is attracted by high volatile emissions that are released by the stumps of freshly cut trees. Once in the clearcuts, the pine weevils lay their eggs on tree stumps where the larvae develop until they reach the adult phase and start feeding, preferentially on the bark of nearby young living trees. In the case of pathogens, in general, the existence of small wounds in the stem or roots, and the availability of stumps created by commercial thinnings and final fellings are essential to initiate new infections through the spread of spores (Isomäki & Kallio 1974; Travadon et al. 2012). Ungulates, due to their size and height, need regenerating forests where the plants have not yet grown tall enough to be out of their reach for browsing. However, for weather-related disturbances, a forest with other characteristics will be more prone to wind damage. For example, a Norway spruce forest is more likely to suffer damage if the trees are tall – over 20 meters – and the evergreen canopy is relatively heavy, thus increasing the wind drag during big storms (Gardiner et al. 2013).

The literature review examining the effects of various adaptation strategies revealed similar trends in certain aspects for forests dominated by

Norway spruce and those dominated by Scots pine (Tables 4 and 5). In general, the adaptation strategy of mixed-species stands with birch mixtures, both for forests dominated by Norway spruce and Scots pine, result in reductions in susceptibility for at least four of the ten disturbances studied. Undertaking few or no thinnings is also connected to reducing susceptibility to four disturbances in Norway spruce-dominated stands, namely, wind, pine weevil, and root rot infections (*Heterobasidion annosum*, *Heterobasidion parviporum*, and *Armillaria* spp.) (Mäkinen et al. 2007; Samariks et al. 2020). However, susceptibility to snow damage increases with a lack of thinnings during the rotation (Hedstrom & Pomeroy 1998). Short rotation periods contribute to increasing forest susceptibility to the largest number of natural disturbances, including pine weevil and three species of pathogens – root rot *Heterobasidion* spp. and *Armillaria* spp. root rot fungus (Gunulf et al. 2013). Nevertheless, short rotations help to reduce susceptibility to damage by wind, snow and SBB (Díaz-Yáñez et al. 2019; Zimová et al. 2020). Long rotation periods, in contrast, increase the susceptibility to damage from disturbances to which the characteristics of mature forest stands are relevant, making the forest more prone to damage from disturbances such as wind and SBB (Overbeck & Schmidt 2012). On the other hand, logging residue removal and prescribed burning generally do not affect forest characteristics and species composition relevant to most natural disturbances studied. Prescribed burning can affect negatively the quality of feeding resources of SBB, thus reducing susceptibility to SBB attacks (Toivanen et al. 2009). However, prescribed burning can create better conditions for the development of pine weevil (Pitkänen et al. 2008). Uneven-aged forestry also contributes to reducing susceptibility to several disturbances. However, it should be noted that for uneven-aged forestry, evidence from field experiments is scarce and therefore it is more difficult to draw conclusions. In contrast, other strategies, such as mixed-species stands, have been studied more extensively and can indicate shifts in susceptibility with greater certainty.

In line with previous studies, such as Pasztor et al. (2015), using adaptation strategies that promote an increase in tree species richness as well as forest structures tends, in general, to decrease susceptibility to a wide range of disturbance agents. The tree species selected for the mixtures is of great importance since many biotic disturbance agents are strongly connected to specific tree species (Vehviläinen & Koricheva 2006).

Understanding the life cycles and resource needs of biotic agents is essential when planning silvicultural practices such that the access and availability of these resources is disrupted (Lygis et al. 2004; Huuskonen et al. 2021). Furthermore, the interactions between disturbance agents are important since both forest susceptibility to other disturbances and forest development can be affected (Ruel et al. 2023). For instance, new pathogen infections can, over time, decrease tree vigour and weaken tree defences, increasing the chance of insect damage such as SBB attacks (Honkaniemi et al. 2017; Ruel et al. 2023).

Table 4. Matrix illustrating the relationship between each adaptation strategy and each natural disturbance in terms of forest susceptibility to damage for a Norway spruce-dominated stand. The colours represent the following: green (arrow down) indicates a decrease in forest susceptibility for a given disturbance when a specific adaptation strategy is applied; orange (arrow up) indicates an increase in forest susceptibility for a given disturbance when a specific adaptation strategy is applied; blue (letter N) indicates no effect on forest susceptibility for a given disturbance when a specific adaptation strategy is applied; grey (letter U) indicates that the literature review did not find any articles covering the relationship between a specific strategy and a particular disturbance; white (dash –) indicates the lack of a connection between an adaptation strategy and a disturbance for a Norway spruce-dominated stand. The strategy of uneven-aged forestry includes selection fellings and patch cutting.

	Norway spruce-dominated forest							
Strategies	Mixture with Scots pine	Mixture with birch	Shorter rotations	Longer rotations	Few or no thinnings	Logging residue removal	Prescribed burning	Uneven-aged forestry
Disturbance								
Wind	↓	↓	↓	↑	↓	U	U	↓
Snow	N	↓	↓	U	↑	U	U	U
Spruce bark beetle	↓	↓	↓	↑	↑	N	↓	↓
European pine sawfly	↑	–	–	–	–	–	–	–
Pine weevil	N	N	↑	↓	U	↓	↑	↓
Root rot (*Heterobasidion annosum*)	N	N	↑	U	↓	N	N	U
Root rot (*Heterobasidion parviporum*)	↓	↓	↑	U	↓	N	N	U
Root rot (*Armillaria* spp.)	↓	↓	↑	U	↓	N	N	↑
Scots pine blister rust	↑	–	–	–	–	–	–	–
Browsing (Ungulates)	↑	↑	U	U	U	↓	N	↑ ↓

Climate change plays an important role in the expansion of forest areas exposed to various disturbance agents, as well as in the development of forests and the life cycles of biotic agents (Ruel et al. 2023). Global warming, combined with extended periods of drought, can reduce forest resistance against various threats and can create favourable conditions for different biotic agents to feed and reproduce. This can lead to increased population sizes of these agents, resulting in greater pressure on host tree species.

Table 5. Matrix illustrating the relationship between each adaptation strategy and each natural disturbance in terms of forest susceptibility to damage for a Scots pine-dominated stand. The colours represent the following: green (arrow down) indicates a decrease on forest susceptibility for a given disturbance when a specific adaptation strategy is applied; orange (arrow up) indicates an increase in forest susceptibility for a given disturbance when a specific adaptation strategy is applied; blue (letter N) indicates no effect on forest susceptibility for a given disturbance when a specific adaptation strategy is applied; grey (letter U) indicates that the literature review did not find any articles covering the relationship between a specific strategy and a particular disturbance; white (dash –) indicates the lack of a connection between an adaptation strategy and a disturbance for a Scots pine-dominated stand. The strategy of uneven-aged forestry includes selection fellings and patch cutting.

	Scots pine-dominated forest							
Strategies	Mixture with Norway spruce	Mixture with birch	Shorter rotations	Longer rotations	Few or no thinnings	Logging residue removal	Prescribed burning	Uneven-aged forestry
Disturbance								
Wind	↑	↓	↓	↑	↓	U	U	↓
Snow	N	↓	↓	U	↑	U	U	U
Spruce bark beetle	↑	–	–	–	–	–	–	–
European pine sawfly	↓	↓	U	U	↑	↓	U	U
Pine weevil	N	N	↑	↓	U	↓	↑	↓
Root rot (*Heterobasidion annosum*)	N	N	↑	U	↓	N	N	U
Root rot (*Heterobasidion parviporum*)	↑	–	–	–	–	–	–	–
Root rot (*Armillaria* spp.)	↓	↓	↑	U	↓	N	N	↑
Scots pine blister rust	↓	U	U	U	N	U	U	U
Browsing (Ungulates)	↓	↑	U	U	U	↓	N	↑ ↓

The scale at which planning, and management are carried out is also of great importance, as the silvicultural practices implemented in a stand not only affect its susceptibility to damage but also impact the neighbouring stands' susceptibility within the landscape. An example of this is browsing pressure on forest stands. If the landscape contains a wide variety of tree and shrub species that are palatable to ungulates, the distribution of browsing damage tends to be more dispersed and not concentrated in a few stands, in which damage to regenerating forests is severe (Bergqvist et al. 2018; Felton et al. 2022a). However, if the landscape is dominated by monocultures, such as Norway spruce, browsing pressure may be concentrated in smaller forest areas or stands containing one or more species preferred by ungulates over Norway spruce (Kuijper et al. 2009).

To conclude, a holistic approach is essential for understanding the complex interactions between forests, disturbances, and climate change. This understanding is essential for implementing silvicultural practices wisely and reducing forest susceptibility to damage from various natural disturbances.

3.2 The impact of forest management strategies on forest susceptibility to the European spruce bark beetle (Paper II)

Paper II evaluated the effect of different forest management strategies on SBB forest susceptibility and the trade-off against harvest volumes. In addition, the effects of applying these strategies on biodiversity were also studied. The management strategies that were evaluated were the following: reference (REF), mixed-species stands (MIX), short rotation periods and no thinnings (SHORT), prolonged rotations (LONG), and continuous cover forestry (CCF) (detailed descriptions in Table 2). This study looked at the development of forest susceptibility to SBB for different harvest volume demands (75, 85, 90, 95, and 100% of the maximum potential harvest level), i.e. the impact of demanding higher or lower harvest volumes during the planning horizon on the forest's susceptibility to SBB attacks was evaluated.

The individual strategy that achieved the lowest forest susceptibility was SHORT, followed by REF and MIX. The SHORT strategy produced the lowest susceptibility values and was also the strategy that achieved the second largest harvest volumes behind REF. On the other hand, MIX resulted in similar but slightly higher susceptibility values compared to REF and, on average, harvest volume yields were 1 to 1.5 $m^3ha^{-1}yr^{-1}$ smaller. LONG and CCF were the strategies that, throughout the planning horizon, resulted in the highest values of susceptibility. In addition, CCF produced the lowest values of harvest volume, approximately 3 $m^3 ha^{-1} yr^{-1}$ lower than REF for the maximum harvest volume demand.

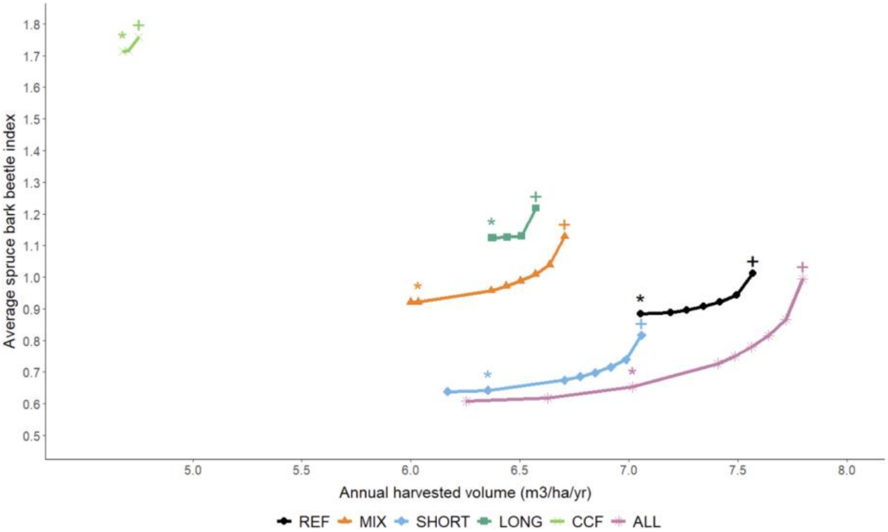

Figure 1. Trade-off curves between the average annual harvested volume and the average SBB susceptibility index over the 70-year planning horizon. Each line represents a management strategy, except for the violet line, which allows for the application of any individual strategy (see Table 2). The symbol “+” indicates the result of maximizing the total harvest volume over the planning horizon without considering the SBB susceptibility index. The symbol “*” indicates the result of minimizing the SBB susceptibility index, subject to a requirement of achieving 90% of the total possible harvest volume.

When maximizing the total harvest volume over the planning horizon without including consideration of the SBB susceptibility index (equivalent to harvest demand 100%), the management strategy used in over 65% of the forest area was REF (Figure 2). In addition, for harvest demand 100%, MIX, SHORT and LONG were also used in smaller portions of the forest area. The maximum demand for harvest volume led to the highest levels of average forest susceptibility to attack by the SBB (Figure 1). However, when harvest volume demands were reduced to allow for a decrease in the forest's average susceptibility to SBB, the proportion of the area where management strategies were applied varied. In this study, the most effective combination of management options to decrease the average susceptibility to SBB at the forest level was to combine SHORT with MIX and REF strategies in different proportions. For a harvest demand of 75%, the SHORT strategy was applied to almost 70% of the forest area, while MIX was used on more than 20%. The remaining forest area was managed with REF, CCF, and a very small proportion with LONG. Reducing the harvest volume demand from 90% to 75% resulted in practically no difference in susceptibility to SBB attack. Therefore, to achieve a substantial reduction in susceptibility, it was unnecessary to drop the harvest volume below 90%, as the reductions in susceptibility at this level were minimal (Figure 1).

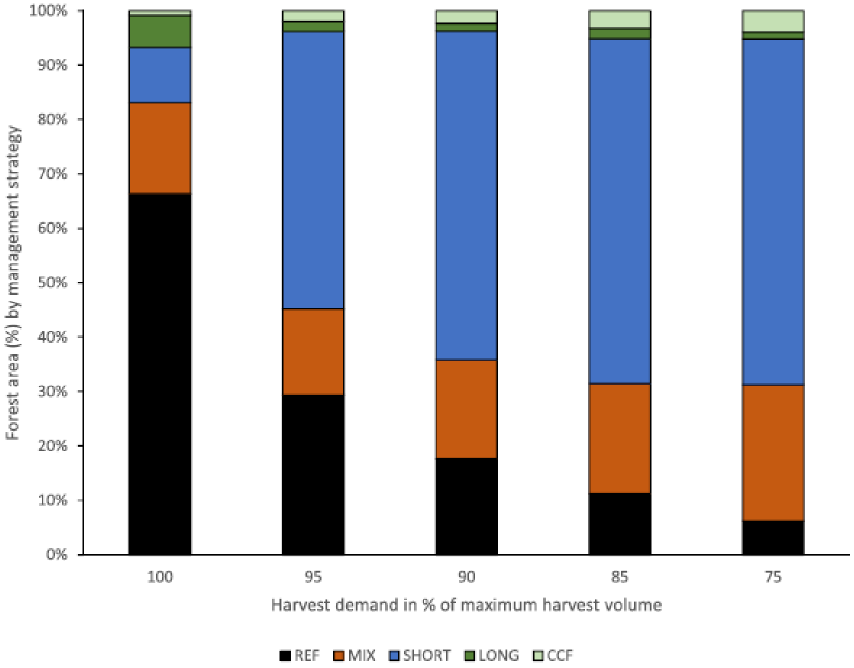

Figure 2. Representation of the percentage of forest area in which each individual strategy is applied to achieve 1) maximizing the total harvest volume over the planning horizon without considering the SBB susceptibility index (harvest demand 100%), and 2) minimizing the SBB susceptibility index, subject to a requirement of achieving 95, 90, 85, and 75% of the total possible harvest volume (x-axis).

One important aspect is the total time over the planning horizon in which the forest has high relative susceptibility levels. This can give an indication of the time during which SBB has the opportunity to use suitable forest resources for breeding. When harvest demands were reduced to 90%, the lowest average of the SBB susceptibility index during the planning horizon was obtained by the SHORT strategy. Following the SHORT strategy, REF and MIX strategies presented similar results to each other and maintained low susceptibility values over the planning horizon. The application of MIX resulted in susceptibility values similar to those of REF because, despite considerably increasing the proportion of tree species other than Norway spruce and reducing the presence of Norway spruce in the forest area, the volume per hectare of Norway spruce remained above 200 m^3/ha, contributing to sustaining a high SBB susceptibility index (see Paper II).

Biodiversity is assessed on the basis of the percentage of forest area older than 120 years, mature broadleaf-rich forest, and the proportion of forest area with large diameter trees (Andersson et al. 2022). The proportion of forest area older than 120 years remained low over the planning horizon for all management strategies and harvest demands. The forest area set aside at final fellings did not have the time to reach 120 years, since the planning horizon was shorter, i.e. 70 years. On the other hand, the proportion of mature broadleaf-rich forest remained low for all strategies except for CCF, where it increased to up 40% of the total forest area. Finally, the proportion of forest area with large trees followed a similar trend to that of mature broadleaf-rich forest: all strategies except CCF exhibited low percentages, while CCF progressively increased the proportion of forest area with large trees to almost 30% by the end of planning horizon.

The management strategies studied led to different forest susceptibility values. The management strategies that had the greatest impact on mature spruce stands – by either reducing their presence through felling or by promoting the presence of other tree species, such as SHORT, REF, and MIX – were those that most effectively reduced the overall susceptibility of the forest. A similar observation was made by Kärvemo et al. (2014), who found that the presence of large timber volumes in Norway spruce trees of sizes suitable for SBB reproduction plays a fundamental role in increasing the chances of SBB infestations. In this study, the CCF strategy does not completely eliminate the presence of Norway spruce trees with large diameters in the forest over the planning horizon, which may explain why the average susceptibility to SBB attacks obtained by applying this strategy remained high throughout. Maximizing harvest volumes influenced the average forest susceptibility values. However, when the forest susceptibility index was minimized subject to a specific percentage of the maximum harvest volume achievable, the influence of harvest demands on susceptibility was very small once reduced to 90% or less. In contrast, the biodiversity parameters assessed did not improve with the management strategies studied, suggesting that their inclusion in the optimization model may be needed to guarantee their improvement in the long-term. To conclude, this study highlights the benefits of diversifying management in an oriented way to reduce overall forest susceptibility to SBB. Moreover, promoting biodiversity may require specific actions beyond those considered in this study.

3.3 A new forest planning model to optimize the landscape configuration to decrease forest susceptibility to European spruce bark beetle outbreaks (Paper III)

In Paper III the development of a new mathematical forest planning model is described. This model is intended to help in generating a forest configuration at the landscape level that reduces the likelihood of SBB population build-up and decreases the chance of large outbreaks. This model includes consideration of economic outcomes (the first term in the objective function) and of three important components at the landscape level that influence forest susceptibility to SBB attacks (the second term in the objective function) (for further details see the methods section 2.4). The three individual components influencing forest susceptibility to SBB that are incorporated into the model are: 1) the average SBB susceptibility of the landscape (estimated with the SBB forest susceptibility index); 2) the distance between forest zones of high susceptibility, those exceeding a threshold value of the susceptibility index; and 3) the total size of highly susceptible forest zones. The weighting of these two terms is modulated by the parameter α which takes values between 0.00 and 1.00. A value of 1.00 gives 100% of the weight to maximizing the economic outcome (first term), and a value of 0.00 gives 100% of the weight to minimizing the SBB forest susceptibility components (second term).

Fast growth of SBB populations is supported, in part, by the least resistant forest stands in the landscape (Seidl et al. 2015), identified in this study as those with index values over an established threshold. The model presented is successful in targeting and reducing susceptible forest stands in the landscape by reducing their availability and spreading them out, thus, creating less favourable conditions for the development of SBB outbreaks.

Development of the objective function components

The results from the four study areas evaluated followed similar trends in the development of the NPV and susceptibility components of the objective function (Figure 3). The first term, corresponding to the NPV, resulted in an upward trend of 5% in the total NPV from $\alpha=0.00$ to $\alpha=1.00$ (Figure 3A). The four study areas exhibited similar upward trends. The second term of the objective function also exhibited a clear tendency towards minimization for small α values (Figure 3B). The average value of the forest susceptibility index showed a decreasing trend from $\alpha=1.00$ to $\alpha=0.00$. The percentage of forest area corresponding to highly susceptible zones also exhibited a decreasing trend from large α values to small α values (Figure 3C). For the large study areas, II, III, and IV, the percentage of highly susceptible area was reduced, in total, by approximately 4%. This reduction went from a starting point of 12% ($\alpha=1.00$) to less than 8% ($\alpha=0.00$) of the entire forest area. Finally, the total distance between highly susceptible zones was considerably reduced with small α values (Figure 3D). This may have been due to the smaller number of highly susceptible zones present, which made the total sum of distance much smaller than that associated with larger α values, resulting in a larger number of highly susceptible zones.

The use of different α values in the objective function had a substantial impact on the results (Figure 3 and 4). Large α values gave greater weight to the first term of the objective function, resulting in the choice of optimal treatment programmes for each stand to maximize the NPV. In contrast, when $\alpha=0.00$, the objective function minimized the second term composed of the forest susceptibility to SBB attack components. The resulting forest landscape had fewer highly susceptible zones, smaller sized highly susceptible zones, and greater distances between them (Figure 4).

Regarding the development of the highly susceptible area over time, both the number of zones and the sum of their total area was, during most simulation years, greater for $\alpha=1.00$ and lower for $\alpha=0.00$ (Figure 4). Similarly, the change in the average susceptibility index exhibited higher values for $\alpha=1.00$ compared to $\alpha=0.00$ throughout almost the entire planning horizon. These values indicate the varying availability of forest resources throughout the planning horizon, with $\alpha=1.00$ maintaining higher average susceptibility levels. These resources are highly susceptible to being utilized by SBB, leading to damage and increasing the likelihood of building up large SBB populations. All the study areas evaluated present similar trends.

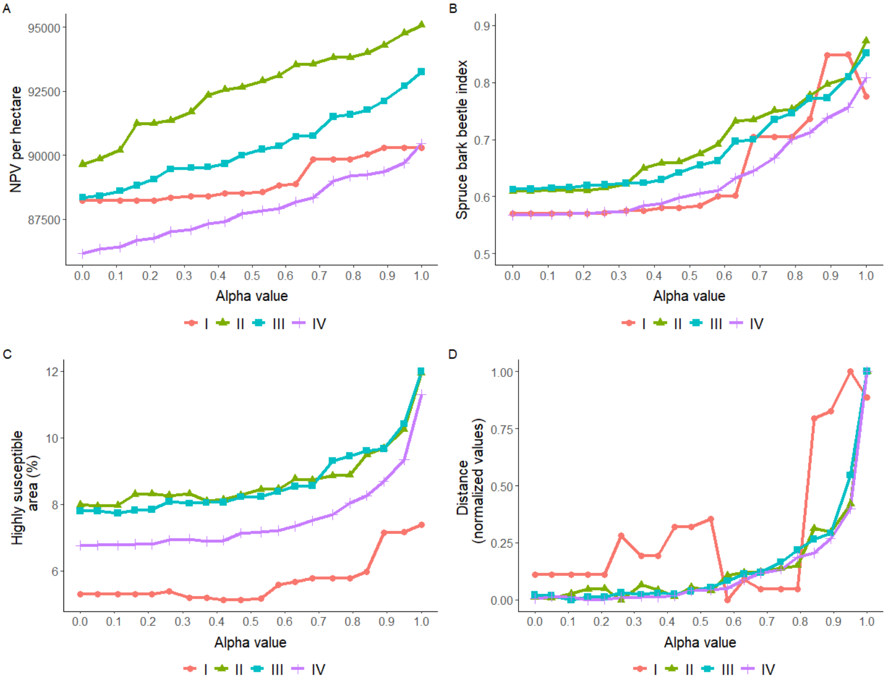

Figure 3. Development of the four components (first term + second term) of the objective function for a range of 20 different α values, from α=1.00 to α=0.00. The first term represents the economic outcome, the NPV per hectare (A). The second term covers three susceptibility components: the SBB susceptibility index (B), the area of forest zones that are above the established index threshold value (C), and the total distance between highly susceptible forest zones (normalized values) (D). Study areas I, II, III, and IV are represented by different colours and symbols.

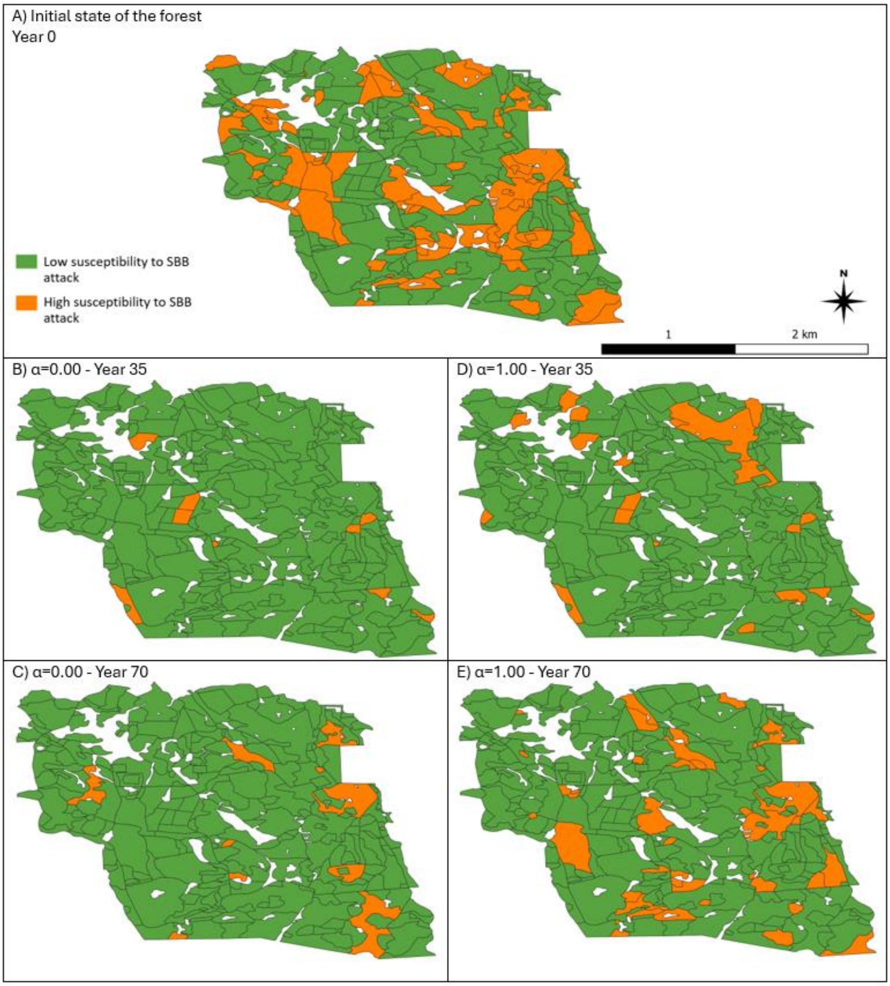

Figure 4. Maps illustrating the change in number and size of highly susceptible forest zones during the planning horizon for two extreme α values, α=0.00 and α=1.00. Green indicates stands with low susceptibility to SBB attack, and orange indicates stands with high susceptibility to SBB attack. Figure 4A shows the initial state of the forest. Figures 4B and 4C show the forest landscape in simulation years 35 and 70 for α=0.00 (minimizing susceptibility to SBB). Figures 4D and 4E show the forest landscape in simulation years 35 and 70 for α=1.00 (maximizing NPV).

Model properties

Most of the problems considered achieved an optimal solution within the established MIP gap (Table 6). However, three problems, corresponding to study area I, for α=1.00, and study area IV, for both α=1.00 and α=0.00, did not reach an optimal solution within the 3600-second time limit set as the stop criterion. The number of variables and constraints shows an increasing trend as the size of the study area grows in terms of the number of stands, indicating that the problem size increases accordingly. Along with this, it is possible to observe a trend in the branch and bound nodes where, in general, the number of nodes explored within the maximum solution time is substantially reduced as the problem size increases.

Table 6. Model properties: the relative MIP gap, number of Branch and Bound nodes, solution times, number of variables and constraints.

Study area	Alpha (α)	Relative MIP gap	Branch and Bound nodes	Solution times (s)	Number of variables	Number of constraints
I	1.00	0.00341	486145	3600	61553	66645
I	0	<0.00001	20446	85	61553	66645
II	1.00	<0.00001	18158	1048	246587	297793
II	0	<0.00001	185092	1564	246587	297793
III	1.00	<0.00001	3379	939	713802	883051
III	0	<0.00001	109742	1870	713802	883051
IV	1.00	0.00001	907	3600	1385249	1730241
IV	0	0.00025	1140	3600	1385249	1730241

Furthermore, the cost of achieving a less susceptible spatial configuration of forest characteristics amounts to 5% of the total NPV, resulting in reductions in susceptibility values of up to 30% for study area IV. The model was able to find optimal solutions for five out of eight problems within an hour and for a quite small MIP gap of 0.00001. However, solution times increased as the problem size grew from the smallest study area of 56 stands to the largest of 290 stands. Nevertheless, both the quality of the solution and the time required to find the optimal solution suggest that this model could potentially be applicable to larger study areas. In addition, increasing the MIP gap or the maximum solution time may enhance the likelihood of finding an optimal solution for larger problems, as well as developing a heuristic to solve it more quickly.

3.4 A new forest planning model to minimize forest exposure to wind damage (Paper IV)

The aim of Paper IV is to present a new landscape level approach to minimize the wind exposure to reduce the chances of suffering wind damage. Storms have been an important natural disturbance in Sweden for many years (Nilsson et al. 2004). In recent years, much forest management to reduce wind damage has focused on implementing measures at the forest stand level. However, landscape configuration and characteristics of stands play an important role in reducing forest susceptibility to wind damage.

With this model, it was possible to find the optimal treatment programme for each stand to achieve the best possible distribution of forest characteristics in each of the stands over the planning horizon. The problem described was formulated as a MIP model. The decision variable Z_{ilp} included in the objective function is responsible for identifying forest edges of stands dominated by Norway spruce that are exposed to the wind. These edges, therefore, are more exposed to damage compared to forest edges of stands that have shelter from other neighbouring stands. Focus was placed on the objective of reducing wind exposure only in stands dominated by Norway spruce, since there is evidence that this tree species is usually more susceptible to wind damage than, for example, birch.

Identifying whether a forest edge is exposed or not to wind damage was carried out using the parameter d. Neighbouring stand edges (i.e. those that share a common perimeter) with a height difference of more than d meters were considered exposed and the variable Z_{ilp} was allocated a value of 1. However, if the difference in height between two neighbouring stand edges was less than d meters, they were not considered exposed and the variable Z_{ilp} was allocated a value of 0. In this study, the model was tested for d values of 5, 10, and 15 meters. In addition, model constraints included an even-flow harvest constraint and NPV demand. In the even-flow harvest constraint, the difference in harvest volume between two consecutive periods could not be more than 20%. The NPV demands that were tested were 70, 80, 90, 95, 96, 97, 98, 99, and 100%. Forest development simulations and optimization were performed with Heureka PlanWise (version 2.17.2.0). Data analyses were performed with Heureka PlanWise and Arc Map 10.7.0. The study area chosen to test the model is located in Småland, southern Sweden. This forest area is partially dominated by Scots pine, 48%, and Norway spruce, 45%.

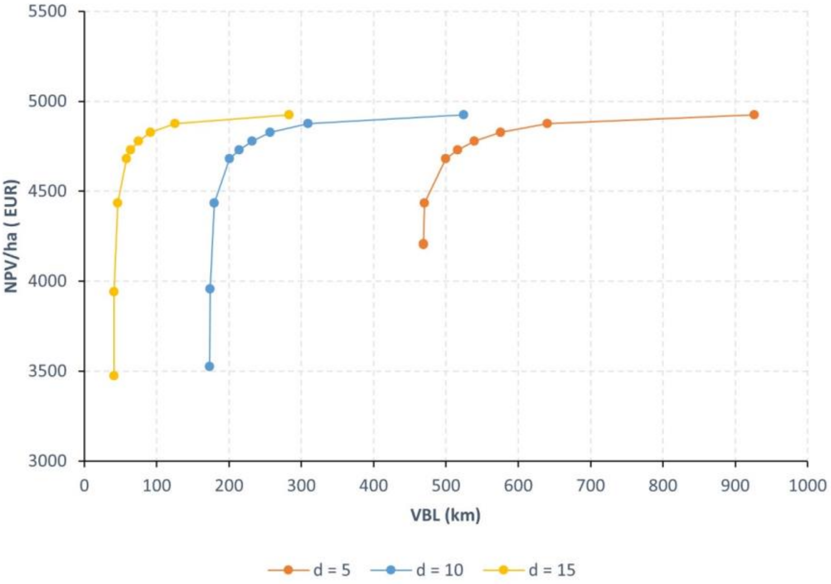

Figure 5. Trade-off curves between NPV and the total length of exposed forest edges in the landscape (VBL). Each of the investigated cases (*d*=5, *d*=10, *d*=15) is represented by a different colour. The points on each curve represent different NPV demands, from the right associated with the maximum possible NPV achievable (NPV100) to the left with the lowest required NPV of at least 70% from the maximum achievable (NPV100).

The results showed that moderate reductions in NPV make it possible to greatly reduce the total perimeter of exposed forest edges at the landscape level (Figure 5). For the case study, *d* = 10 meters, an NPV demand of 99% resulted in a reduction of the total length of exposed forest edges by 41%. Further reductions, down to 90% NPV demand, were able to reduce the exposed forest edges by 65%. However further lowering of the NPV demands produced only very small reductions in exposed forest edges. Increasing or decreasing NPV demands in turn influence the total harvested volume where, in general, larger NPV demands lead to larger harvested volumes and vice versa. For example, in the extreme case where the NPV demand was 70%, the total harvested volume was 35% less compared to the volume obtained with the highest possible NPV over the last 25 years of the planning horizon. One result derived from this model was the aggregation of stands of similar heights i.e. height differences lower than the chosen *d* value. This also resulted in postponing some final fellings to avoid the creation of new forest edges over the planning horizon and led to an increase in the total area older than 80 years (Figure 6).

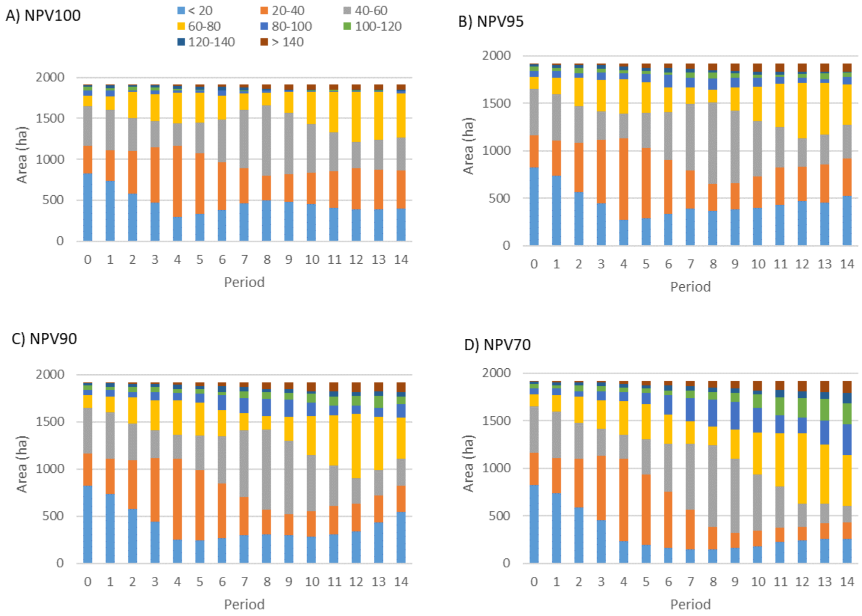

Figure 6. Distribution of area by age class and per period for case *d*=10. The NPV demands presented are NPV 100 (A), NPV 95 (B), NPV 90 (C), and NPV 70 (D).

The results obtained in this study were similar to previous studies in which the reduction of wind exposure in the landscape has also been addressed (Zeng et al. 2007; Heinonen et al. 2009). As the demand for NPV is reduced, height differences greater than *d* at the landscape level are reduced. The selection of different values of *d* has a large impact on the identification of exposed forest edges. Smaller values of *d* considerably increase the total perimeter that is considered exposed to wind damage, and vice versa. Furthermore, final fellings have a tendency to be postponed and the landscape develops an aggregated distribution of stands with similar heights (Figure 7). This model, solved with exact methods, can offer forest owners more options and flexibility when deciding how much to invest economically, in relation to reducing NPV demand, to achieve a forest landscape less exposed to wind damage.

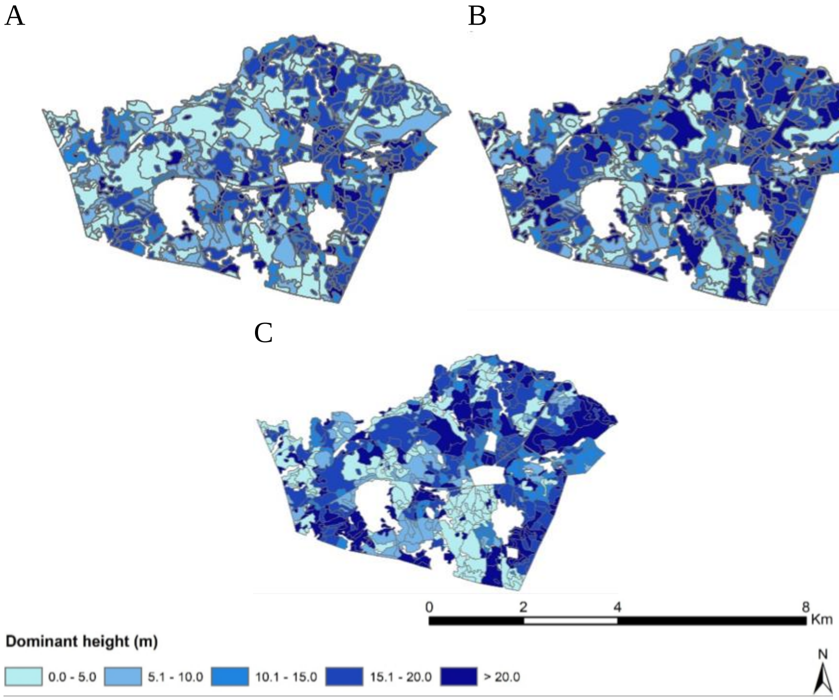

Figure 7. Dominant height distribution in the landscape. Three maps are presented: the initial state of the forest in period 0 common for all cases (A), maximization of NPV (NPV 100) for case *d*=10 and period 14 (B), and minimization of the length of exposed forest edges in the landscape for case *d*=10 and period 14, for a NPV demand of 95% of the maximum achievable.

4. Discussion and reflections

This thesis presents compelling examples of how planning can be used to increase the potential of management to reduce the susceptibility of forests to disturbance damage. It contains analysis of the current synergies and trade-offs within well-known adaptation strategies in forest management to reduce disturbance damage. Understanding how forest management can alter the forest characteristics and species composition that underlie various natural disturbances (Paper I) is essential for developing strategies that create forests less susceptible to abiotic and biotic disturbances (Papers II, III, and IV). Forest planning can inform forest management on how to create and maintain specific predominant forest characteristics that reduce susceptibility to damage from particular disturbances (Papers II, III, and IV). The integration of actions to create specific spatial components into the forest planning process contributes to transforming large forest areas, making them more resistant to various types of forest damage and to changes resulting from climate change.

4.1 Forest management planning as a guide for overall management direction

Forest planning provides the basis for all decisions made in forest management. Planning is essential for building the knowledge on which the decision-making process is based, i.e. planning contributes to making informed decisions about implementing specific actions to achieve desired conditions in the forest in the short-, medium-, and long-term (Holsapple 2008). In Figure 2, Paper II, an indication is presented of which management strategies should be predominantly implemented in the forest to reduce levels of susceptibility to SBB attack. Figure 2 also presents different ratios of management strategies for a range of harvest volume demands. Figure 1, in contrast, shows the potential development of forest susceptibility if each of the management strategies were applied individually. These types of information and analyses are useful as they indicate possible trends of change and potential costs associated with them i.e. if a specific strategy is chosen, certain forest characteristics will be promoted leading to changes in forest susceptibility at some cost. Adapting forest management to reduce overall susceptibility to disturbances incurs costs that are worth estimating (European Environment Agency 2022). However, it is challenging to calculate the economic impacts of adapting management (IPCC 2023). Many studies and reports suggest that the cost of adapting forest management is probably less than the cost of inaction (Parry et al. 2009; Valverde et al. 2022). Parry et al. (2009) suggests that, adapting forest management could avoid up to 80% of the costs of potential impacts. The results of this thesis show that forest management adaptation can help reduce forest characteristics influencing susceptibility to damage. In relation to the cost of adapting management at the landscape level (Papers III and IV) or at the county level (Paper II), this typically ranged between 5 and 10% of the total NPV benefit or harvest volume. In addition, the gain in terms of susceptibility reduction, quantified in Papers II and III using the SBB susceptibility index and in Paper IV as the total length of forest edges, is substantial.

In the forestry field, achieving almost any kind of objective requires specific actions and plans that include a long-term perspective (Hynynen et al. 2015). Paper II presents an analysis for Norway spruce-dominated stands at the county level suggesting that it takes several decades to substantially increase the proportion of mixed-species in a forest that is currently dominated by planted monocultures. Thus, increasing mixtures to contribute to reducing forest susceptibility to SBB should be planned with adequate time. This information can offer a temporal scale to decision makers and highlight the importance of planning ahead in forestry. Another interesting example of considering the time perspective in forestry is provided by Eggers et al. (2024), who point out that it would only take 15 years to increase the forest area with ground lichen, used by reindeer herders, by 22% if appropriate management was implemented. In forestry, a common example of temporal scale among decision makers is ensuring the sustainable use of forest resources and maintaining the provision of ecosystem services over time, which requires long-term planning.

The planning models developed in the research described in this thesis enable us to simulate forest development, evaluate different management alternatives, and create various scenarios accounting for natural disturbances in terms of forest characteristics influencing the susceptibility to damage. They also allow us to investigate the consequences of promoting specific forest characteristics and studying the trade-offs between various objectives, among other possibilities. In this thesis, Paper II describes the simulation of forest development for five different management strategies and evaluates their effects on the total harvest volume and the average forest susceptibility to SBB over a planning horizon of 70 years. The results of the study show the individual strategy that performs best (SHORT), but it is a combination of management strategies that is the best option to follow in order to achieve the lowest SBB susceptibility levels. Simulation of forest management has been connected to many other aspects in previous studies, including reindeer husbandry, carbon sequestration potential and climate change (Chen et al. 2000; Linder 2000; Korosuo et al. 2014).

The objectives and methodology of Papers III and IV highlight the importance of understanding, in detail, the characteristics of a forest that make it susceptible to disturbances. In these studies, the objectives can be defined as “minimize or maximize specific forest features” to change forest susceptibility to different disturbances. This approach requires that forest susceptibility can be determined on the basis of forest variables. For example, the quantification of susceptibility can be achieved through indices built on one or several forest parameters (Papers II and III), or directly via forest variables inherent to the forest, such as the total size of highly susceptible zones to SBB attack (Paper III) or the total perimeter of forest edges exposed to wind (Paper IV). Paper I offers a compilation of forest characteristics that influence forest susceptibility to each major disturbance considered. Furthermore, it describes the connections between these forest characteristics and how forest adaptation strategies can change specific forest characteristics to reduce susceptibility to damage. Paper I can serve as support to identify and develop approaches to include those variables that are relevant to each disturbance when adapting management to reduce forest susceptibility.

Considering biotic agents, however, requires a deep understanding of 1) their life cycles and how they utilize the available resources in the forest to survive, 2) what host-agent interactions there are, and how host selection occurs, 3) how environmental conditions affect both the hosts and the biotic agents, and 4) how landscape characteristics influences forest susceptibility to damage (Malmström & Raffa 2000). Each biotic agent has its own habitat preferences and a specific way of utilizing the resources available in the forest. Having a good understanding of these issues is advantageous when planning forest management aimed at reducing damage from biotic agents. These aspects were considered when conceptualizing Paper III in connection with SBB ecology and how SBB utilizes forest resources at an early stage of an outbreak as well as during an ongoing outbreak. Appropriate management planning can contribute to reducing the availability of resources that biotic agents need to reproduce and survive. Furthermore, planning can promote the fragmentation of habitats that can potentially be used by biotic agents. In many cases, it is difficult to eliminate damage completely, however, forest planning can contribute to disrupting the uncontrolled build-up of SBB populations that eventually give rise to major outbreaks (Seidl et al. 2015). Paper III targets both stand and landscape aspects that are important for SBB in the stages of early outbreaks or during ongoing outbreaks, by greatly reducing the connectivity of resources available.

4.2 The importance of incorporating spatial variables in forest planning

There is evidence showing that intensively managed forests have a tendency to be more susceptible to various disturbance damage than those forests that are not (Wolf et al. 2023). Proper forest management planning offers numerous opportunities to develop the key forest characteristics and species compositions necessary to reduce susceptibility to disturbances. Paper I highlights some of these characteristics for a range of nine different disturbances. Furthermore, Papers III and IV exemplify the potential of forest planning to target specific forest characteristics that are critical to particular disturbances, and to change these forest characteristics in a generalized manner to create a forest landscape that is less susceptible to damage. A similar approach to the one in Papers III and IV was implemented by Minas et al. (2014), where a MIP model was developed to create and maintain more desirable fuel patterns in the landscape, thereby reducing susceptibility to fire damage. Forest planning can be applied at different spatial scales depending on the objectives defined for the forest (see section 1.4). However, for natural disturbances, the management that is chosen and applied to an individual stand in a landscape can influence the susceptibility to damage of other stands within the same landscape (Kolström et al. 2011). This is demonstrated in Paper III, where the implementation of the same management alternatives at different spatiotemporal scales affects susceptibility in opposing directions (Figure 4). In addition, Paper IV clearly presents how the management applied to a stand directly affects the creation of new forest edges around it. Furthermore, the same management alternatives selected and executed differently in space and time for the same landscape can result in very different lengths of exposed forest edges (Figure 5). In other words, forest management at the stand level can be very useful to achieve certain objectives, but when it comes to natural disturbances, an approach with larger scales, including landscape or regional levels, is typically needed (Lindner 2007). Other research studies visualizing the importance of spatiality when addressing natural disturbances, such as wind or forest fires, have also been conducted (Cabeza et al. 2010; Zeng et al. 2010; Minas et al. 2014; Belavenutti et al. 2023). Hlásny et al. (2019) highlight the importance of forest management planning at the landscape level in reducing overall susceptibility to damage by SBB from an ecological perspective. Paper III considers spatial relations of different forest stands, such as the size of highly susceptible forest zones or their proximity, to achieve a forest configuration that weakens the support for SBB population growth.

Furthermore, spatial forest planning has been used in numerous studies where different ecosystem services were accounted for (Baskent et al. 2024). Introducing spatial variables into the models makes them more complex to solve; however, Paper III and IV demonstrates that it is possible to develop planning models that include spatial aspects and still obtain robust solutions within a reasonable amount of time (Table 6).

4.3 Linear programming and mixed-integer programming models: advantages and limitations

In the research underlying this thesis, LP (Paper II) and MIP (Papers III and IV) models were developed and implemented in the DSS Heureka. Paper II focused on optimizing the use of management strategies to reduce the overall average susceptibility of the forest area under study. The problem addressed in this study was formulated as a LP type 1 Model (Johnson & Scheurman 1977). The decision variable x_{ij}, defined as continuous, could take values between 0 and 1. This variable defines the proportion of each management unit area (in this study, NFI plots) to which a specific treatment programme is assigned. This means that each management unit can be divided into several parts, with each part assigned to a different treatment programme. Typically, in practice, stands are not divided into smaller parts with different management strategies applied to them, except, for example, in cases where a stand contains a particular area of high ecological value. Generally, stands represent areas of forest with fairly uniform conditions, in which the same treatment is applied throughout the entire area. However, establishing the decision variable as continuous makes it possible to formulate the problem as a LP problem, which is an advantage since LP problems are often much easier to solve compared to e.g. MIP models. One drawback, though, is that formulating the model as a LP does not allow spatial aspects to be taken into account.

In Papers III and IV, the decision variables included in the models are binary integer variables. Formulating a model with MIP has its advantages, such as the definition of binary variables to help model “yes” and “no” decisions. These models mathematically require many more calculations to find a solution compared to LP models similar in size. So far, the most successful method for solving a MIP model with adjacency constraints is the branch and bound algorithm (McDill & Braze 2001), used in both Paper III and Paper IV. One aspect to consider when formulating a problem as a MIP is its size, relative to the number of variables and constraints included in the model. The size of a MIP has a direct impact on the time needed to find a feasible solution to the problem. As seen in Paper III, the larger the study area, the longer it takes to find a solution to the problem. However, the problem has to be very big to increase the solution time sufficiently to look for alternative methods to address it. In Paper III, it was possible to obtain an optimal solution to a problem with over 710,000 variables and 880,000 constraints in less than one hour and for a MIP gap below 0.0001%. If MIP models contain a sufficient number of variables and constraints to make a problem unsolvable in a reasonable amount of time, it is possible to be less restrictive with the MIP gap, allowing a larger gap between the LP relaxation and the optimal MIP solution. An alternative to increasing the MIP gap would be to develop a heuristic to find an appropriate solution in a reasonable amount of time. Heuristics represent a different approach to finding a solution to an optimization problem, especially in cases where the problem cannot be solved with an exact method in a reasonable amount of time (Lockwood & Moore 1993). Heuristics do not guarantee that an optimal solution will be found, but can identify sufficiently good solutions in much less time. In addition, the quality of the solution can vary and how far a solution is from the optimal one is not known. Despite these drawbacks, heuristics are widely used for large and complex problems (Baskent et al. 2024). Many examples of heuristics can be found in the forest planning field, also applied to disturbance management (Bettinger et al. 2002; Zeng et al. 2010). The most common heuristics used are simulated annealing and tabu search, while less frequently used heuristic methods include genetic or ant colony algorithms (Baskent et al. 2024). However, in Sweden there is still no DSS available that allows the implementation of a heuristic model to solve forest planning problems.

4.4 The complexity of modelling to include susceptibility to disturbance damage in forest planning

Forest planning can cover many types of problem that are difficult to define, model, and solve, for example, climate change, natural disturbances, and biodiversity (Hilborn & Mangel 1997; Pasalodos-Tato et al. 2013; Chudy et al. 2016). In Paper III, aspects related to the ecology of the SBB and the factors that can contribute to increasing the possibilities of outbreaks developing at the landscape level were considered. Including all these aspects in a single model increases its complexity and can make its solution more challenging, as can be seen in the number of variables and constraints. In many cases, it is difficult to include all the relevant aspects from an ecological point of view in a model. Often, the mathematical formulation of the problem has to be as close as possible to real life, but leave some aspects out, to have a chance of finding a solution to the problem. For example, the

Paper III model could be expanded by including aspects related to new forest edges, which tend to be sunnier and warmer places, which SBB prefer when colonizing trees. The model can always be improved and made more complete. However, a small improvement can result in a problem that is difficult to solve and, instead of contributing to finding better solutions, the problem becomes impossible to solve (Baskent & Keles 2005; Borges et al. 2017).

It is also important to remember that the type of solutions that were obtained to the problems posed in Papers II, III, and IV are not exact and precise, but rather give an indication of what type of management has the greatest tendency to take us towards the defined objectives. They indicate the direction of change that it is possible to pursue when adopting certain types of management. Typically, the results give a simplified picture, loosely representing reality, since the models used to carry out the simulations of data from the DSS Heureka as applied here are based on deterministic values (Lämås et al. 2023). This approach to modelling the relationships between environmental variables is quite common (Jackson et al. 2000). However, many processes cannot be modelled accurately due to their variability or because not all details are known (e.g. natural mortality). As a result, simulations of forest management or the impact of natural disturbances on forests may not be accurate (Burgman 2005; Hanewinkel et al. 2011). For this reason, the results of the studies in this thesis should be interpreted as 'directions of change' or 'possible trends' towards specific conditions, rather than as precise predictions of what will occur.

In the simulations conducted, NPV and harvest volume have been estimated for various alternatives. These estimates are based on the assumption that forest growth and production are not affected by climate change, adverse weather events, or natural disturbances that can occur in reality. In this way, the results obtained could be considered 'optimistic results', representing ideal conditions where there is minimal variability and no natural disturbances affecting tree production or mortality. Under such circumstances, the production values are high. Furthermore, the growth models included in Heureka are based on empirical data derived from past growth trends and are largely based on even-aged forest management practices. The latter implies that the forest simulations presented in Paper II for CCF may be less accurate than simulations based on models representing even-aged management, primarily due to the limited empirical data available in Sweden for accurately simulating growth under CCF management.

Climate change, however, is already affecting current forest growth, which is something that is yet not reflected in these growth models. Climate change is, in itself, a source of uncertainty and, in addition to impacting tree growth, it also influences the frequency and intensity of natural disturbances affecting the forest. However, it is reasonable to assume that over the lifespan of the trees in a stand, there will be years of both better and worse growth, along with ongoing exposure to damage and mortality from natural disturbances. As a result, the actual NPV and harvest volume values used in Papers II, III, and IV are likely to be somewhat lower in reality than the simulated values.

Uusitalo et al. (2015) propose several methods for addressing uncertainty in deterministic models, including sensitivity analyses, which were applied in Papers III and IV within this thesis. Sensitivity analyses consist of analysing how the output of the model varies if the value of a parameter is modified within a range of possible values that it can take (Saltelli et al. 2000). For example, in Paper IV a sensitivity analysis was carried out for parameter *d*, which influenced whether a forest edge was identified as exposed or not. In this analysis, it was easy to see that the lower values led to the identification of many more exposed forest edges than the higher values. In Paper III the model was applied to different forest landscape sizes to evaluate the time needed to find solutions as the size of the problem increased.

4.5 Conclusions and future research

This thesis has two main aims, first, to identify the links between disturbance damage and forest characteristics and species composition (Paper I) and, second, to develop new forest planning models to evaluate how management can reduce overall forest susceptibility to wind and SBB damage (Papers II, III, and IV). Climate change is likely going to increase the exposure of the forests to some natural disturbances benefiting from global warming, for instance, as well as affecting the frequency and magnitude of impact of them. In this context, this thesis offers support to decision makers within forestry on the possibilities of adapting forest management to a variety of natural disturbances.

Paper I shows some of the most important relationships between forest characteristics and species composition determining the forest susceptibility to damage to a variety of natural disturbances. Each natural disturbance has its own particularities, for example, the susceptibility to the weather-related disturbances studied is greatly influenced by some of the characteristics of mature forests such as the height or the size and weight of the canopy. However, when it comes to the biotic agents studied, understanding how they use forest resources during their life cycles is important to know what forest characteristics or species might be exposed to be utilized by them. For example, pathogens need stumps or stem wounds to spread and start new infections in the forest. In addition, Paper I highlights the possibilities that exist to target one or several disturbances through diversifying forest management. The development of the models in Papers III and IV has been based on Paper I.

Formulating planning problems using LP offers flexibility to explore forest management impacts on susceptibility over large areas (Paper II). However, when landscape configuration becomes important, spatial complexity increases, requiring MIP formulations (Papers III and IV) or heuristics for solving complex problems. Since many disturbances are linked to spatial characteristics, modelling forest characteristics and species composition at the landscape level effectively reduces factors contributing to forest susceptibility (Papers III and IV). Problems formulated as MIP models can grow a lot in terms of variables and constraints when applied to large forest areas, and this can limit their usability. However, in Papers III and IV, despite the considerable size of the study areas, the branch and bound algorithm was able to find an optimal solution within a reasonable time. This suggests that, while MIP models have their limitations, these models can still be effectively used for relatively large forest areas before the solving time becomes excessively long.

Incorporating uncertainty into planning may necessitate the use of methods different from those presented in this thesis. The uncertainty associated with forest development, natural disturbances and climate change is a critical factor to consider in future studies. Implementing stochastic modelling techniques and conducting sensitivity analyses are effective ways to account for uncertainty from various sources and evaluate its impact on the results. For instance, evaluating the effects of various potential climate change scenarios on forest growth and, consequently, on its vulnerability to natural disturbances is of great importance.

In relation to economic outcomes, Papers II, III, and IV suggest that the necessary investment in terms of NPV or harvest volume reduction for adapting forest management to disturbances does not need to be excessively large. It is possible to reduce susceptibility-related characteristics with modest reductions, approximately 5 to 10%, of the total NPV or harvest volume.

To conclude, this thesis demonstrates that well-oriented forest management planning has the potential to generate appropriate spatial forest characteristics in the landscape over time, which can help to create more forests that are more resistant to disturbances and at a moderate cost.

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Popular science summary

In recent years, there has been a growing emphasis on the opportunities that forests can offer to help mitigate climate change, as well as their ability to provide ecosystem services (useful outputs from natural systems) in a sustainable manner. All of this has led to an increased interest in the resources and products that can be obtained from forests and on how forest management needs to be adapted. In this context, climate change and natural disturbances have become especially important. Both climate change and natural disturbances can have negative effects on forests, affecting their growth and increasing mortality. Climate change is important because it not only influences the growth of trees, but it can also influence the frequency and magnitude of damage caused by natural disturbances. When this damage is very severe, the provision of different ecosystem services is put at risk. One ecosystem service that is highly valued in forests in Sweden is timber production. In many cases, the reduction in timber production would be larger if adapted management is not implemented.

In this thesis, special emphasis was placed on understanding what characteristics make forests susceptible to damage by major natural disturbances in Sweden. Using this knowledge, new approaches were implemented defining goals and restrictions using mathematics with the aim of shaping and creating specific forest characteristics in the landscape that would be less prone to damage. The forest planning models have been developed specifically to reduce forest susceptibility in the landscape to European spruce bark beetle and wind damage.

During its life cycle, the spruce bark beetle utilizes mature Norway spruce forests containing trees with large diameter trunks for breeding and feeding. Forest management aimed to remove or reduce the extent of forests with the characteristics often utilized by spruce bark beetle should predominate in order to reduce the area in which the beetles can thrive. In this thesis, management strategies such as shorter rotation periods or mixed-species stands have been found to be suitable options to reduce the overall susceptibility of the forest to spruce bark beetle attacks. Reducing the volume of Norway spruce per hectare in favour of other tree species may reduce the chance of infestation. Furthermore, the spatial distribution of these characteristics in the landscape influences the build-up of spruce bark beetle populations before and during outbreaks and this has also been addressed in this thesis. Limiting the availability and the proximity of mature Norway spruce stands with large diameter trees contributes to reducing the forests' susceptibility to spruce bark beetle attacks. The focus was placed on the size of highly susceptible forest areas as well as their proximity to each other, with the objective of reducing their size and spreading them out as much as possible in the landscape. To achieve this, a new planning model was developed in order to find the best possible combination of management for each stand in the landscape that would generate a spatial configuration with lower susceptibility to spruce bark beetle attacks.

Regarding wind damage, mature forest stands are, in general, more susceptible to damage than other types of stand. Mature forests are usually taller, with heavy crowns that increase the chances of wind damage. Furthermore, evergreen coniferous species such as Norway spruce, keep their leaves during the autumn and winter, which is the time of the year with the highest concentration of storms, thus increasing their chances of damage during windstorms. In this thesis, assessing forest susceptibility to wind is based on forest edges exposed to wind. Limiting and reducing the length of these forest edges at the landscape level would contribute to reducing forest exposure, thus decreasing forest susceptibility to damage. To achieve this, a planning model was developed that would, over the time window considered, create forest stands that provide shelter to protect each other from wind damage.

In conclusion, there is substantial evidence, including the findings presented in this thesis, suggesting that forest management planning is probably an important tool to create forests with characteristics that will improve their resistance to a wide variety of natural disturbances. To achieve this, forest planning needs to have robust knowledge to be able to target the most important characteristics to create more resistant forests.

Populärvetenskaplig sammanfattning

Skogen som en resurs för att mildra klimatförändringarna samt skogens möjligheter att på ett hållbart sätt tillhandahålla olika ekosystemtjänster (användbara resurser från naturliga system) har rönt stort intressen under senare tid. Sammantaget har detta lett till ett ökat intresse för hur skogsskötseln kan behöva anpassas. I detta sammanhang har klimatförändringar och naturliga störningar blivit särskilt viktiga eftersom de kan ha negativa effekter på skogarna genom att t.ex. påverka deras tillväxt. Klimatförändringarna kan dessutom påverka frekvensen och omfattningen av skador orsakade av naturliga störningar. Vid allvarliga skador riskeras skogens förmåga att tillhandahålla olika ekosystemtjänster. Ett exempel på en högt värderad ekosystemtjänst från svensk skog, som kan påverkas negativt om skogsskötseln inte anpassas till förändringar av klimatet, är produktionen av timmer och massaved.

I denna avhandling har särskild vikt lagts vid att förstå vilka egenskaper som gör skog känslig för skador av stora naturliga störningar i Sverige. Med hjälp den framtagna kunskapen formulerades nya mål och begränsningar i matematiska planeringsmodeller för att skapa specifika egenskaper i skogslandskapet, egenskaper som gör skogen mer motståndskraftig mot skador orsakade av störningar. De planeringsmodeller som har utvecklats avser specifikt att minska skogens känslighet för skador orsakade av europeisk granbarkborre och av vind.

Under sin livscykel använder granbarkborren gamla grovstammiga granskogar för att skapa nya generationer barkborrar. För att minska barkborrekskador bör skogsskötseln syfta till att ta bort eller minska arealen av den skog som barkborren föredrar. I den här avhandlingen har sådana strategier använts för att anpassa skötseln. Till exempel har kortare omloppsperioder och bestånd med blandade trädslag visat sig vara lämpliga alternativ för att minska skogens känslighet för barkborreangrepp. Att minska mängden gran till förmån för andra trädslag kan minska risken för angrepp. Dessutom påverkar den rumsliga fördelningen av bestånd med olika egenskaper i landskapet uppbyggnaden av populationer av granbarkborre, vilket också beaktas i avhandlingen. Att begränsa arealen och närheten mellan gamla grovstammiga granbestånd bidrar till att minska skogarnas mottaglighet för angrepp av granbarkborre. För att uppnå detta utvecklades en ny planeringsmodell för att hitta bästa möjliga kombination av skötsel för varje bestånd i landskapet i syfte att generera en rumslig fördelning som minskar känsligheten för barkborreangrepp. Fokus i den nya planeringsmodellen lades på att minska storleken av mycket mottagliga skogsområden samt sprida ut dem så mycket som möjligt i landskapet.

När det gäller vindskador är gamla skogsbestånd generellt sett mer känsliga för skador än andra typer av skogar. Gamla träd är vanligtvis högre, med stora trädkronor som ökar riskerna för vindskador. Dessutom behåller vintergröna barrträd som gran sina barr under hösten och vintern, dvs den tiden på året med störst frekvens av stormar. De vintergröna träden ökar därmed risken för vindskador jämfört med trädarter som fäller sina löv eller barr. I denna avhandling baseras bedömningen av skogarnas känslighet för vind på förekomsten av vindutsatta skogskanter. Att på landskapsnivå begränsa och minska längden av känsliga skogskanter minskar mängden exponerad skog och därmed också skogens känslighet för skador. För att nå detta utvecklades en planeringsmodell för att bestämma optimal skötsel för varje bestånd i landskapet i syfte att undvika att de skapas nya känsliga skogskanter. I stället fungerar beståndsgrannar som vindskydd i större utsträckning under den tidsperiod som skötselplanerna omfattar.

Sammanfattningsvis finns det betydande belägg för - inklusive resultaten som presenteras i denna avhandling - att skoglig planering som kan identifiera optimal skogsskötsel på bestånds och fastighetsnivå är ett viktigt verktyg för att skapa skogar som leder till skogar med förbättrad motståndskraft mot en mängd olika naturliga störningar. För att uppnå detta behöver den skogliga planeringen baseras på gedigna kunskaper och fokusera på de egenskaper som är mest centrala för att skapa mer motståndskraftiga skogar.

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

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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

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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.

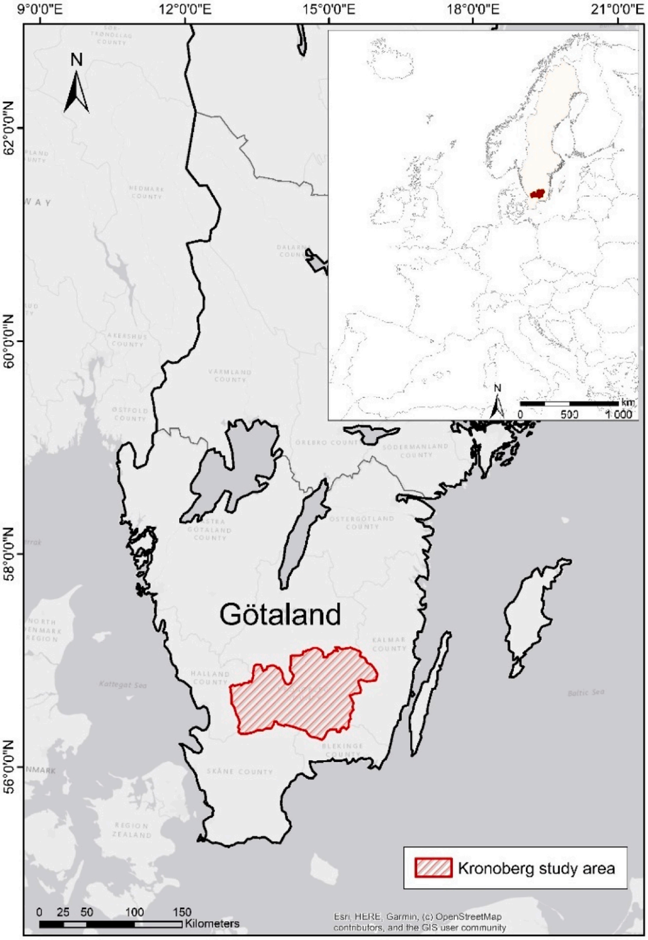

Fig. 1. Map of Kronoberg study area situated in Götaland region, Southern Sweden. The large grey areas within the country represent lakes.

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

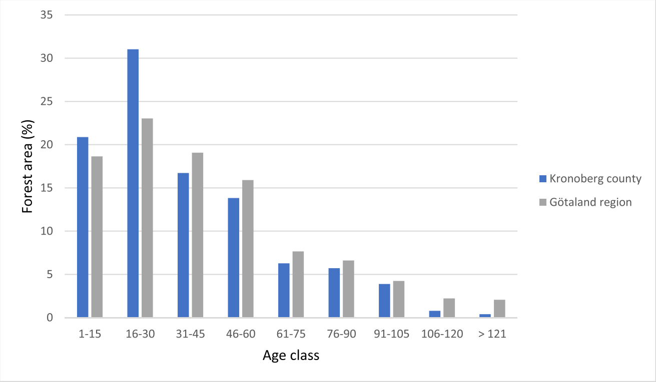

Fig. 2. Initial age class distribution for Norway spruce dominated forest (368 041 ha) in Kronoberg county, Götaland region (see Fig. 1).

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^{3}ha^{-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%.

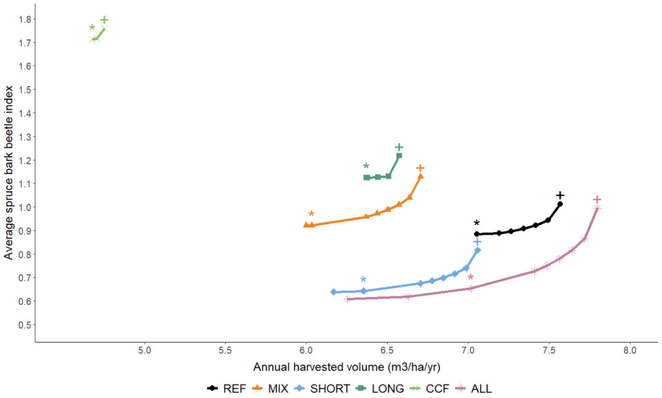

Fig. 3. Trade-off curves between harvested volumes within the 70-year planning horizon and average value of the SBB susceptibility index over the planning horizon. Each line represents an individual management strategy except for the violet line, which represents the combined strategy ALL, where treatment 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.

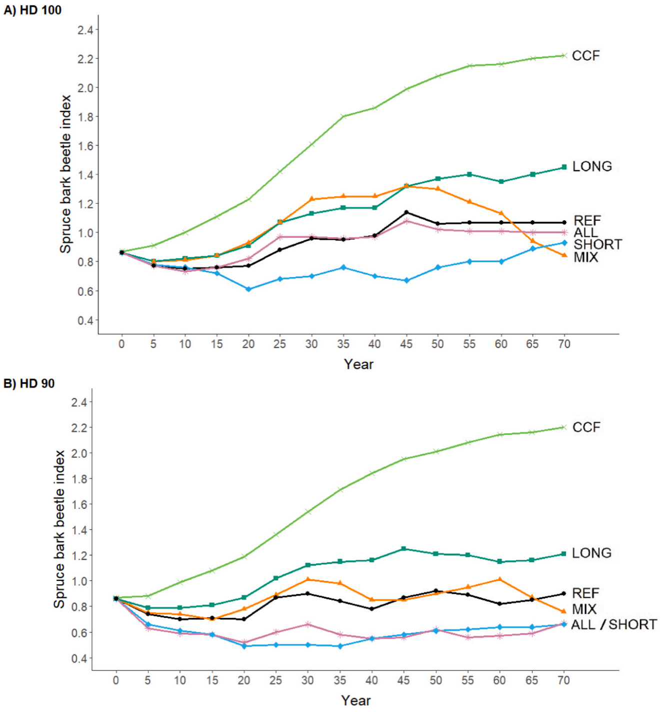

Fig. 4. Development of average value for SBB index during the planning horizon of 70 years and for every strategy. The development of the index is shown for harvest demands (HD) 100 (upper panel) and 90% (lower panel).

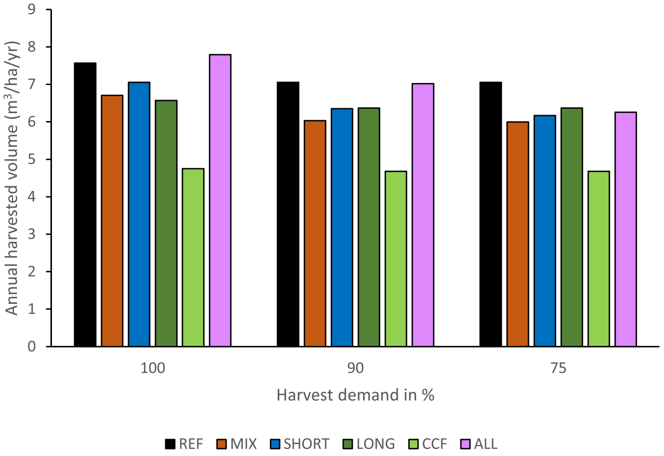

Fig. 5. Average annual harvested volume ($m^3ha^{-1}yr^{-1}$) for the management strategies during the 70-year planning horizon. In all management strategies (see Table 1 for detailed description), the objective was set to minimize the spruce bark beetle susceptibility index subject to a harvest demand 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.

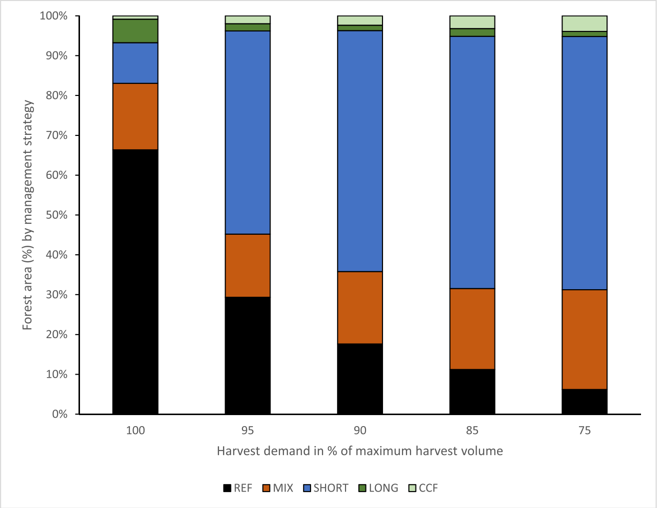

Fig. 6. Percentage of forest area that is subjected to each individual forest management strategy when the combined strategy (ALL) is applied. The distribution is shown for different harvest demands. See Table 1 for a description of forest management strategies.

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

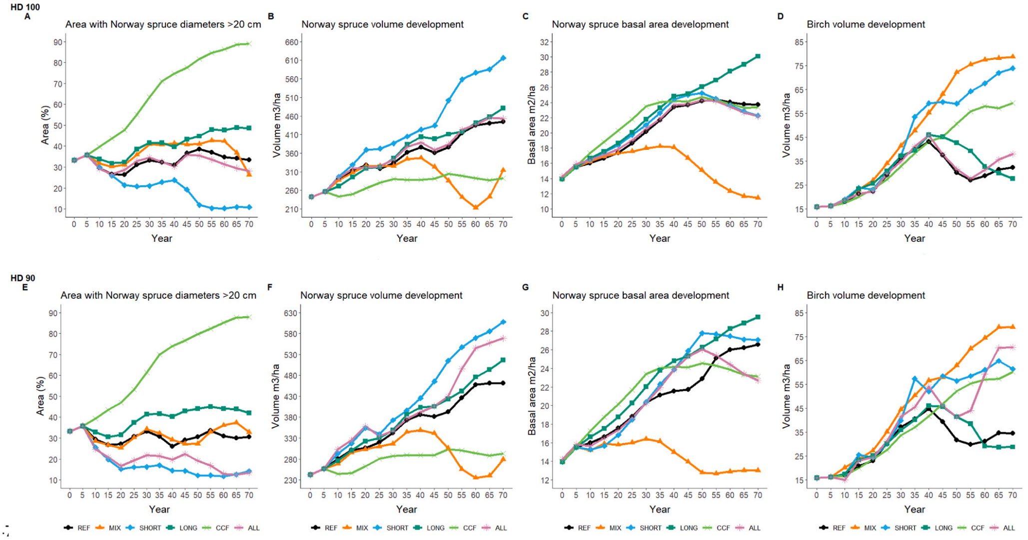

Fig. 7. SBB index parameter development over the 70-year planning horizon. The most important spruce bark beetle index parameters contributing to high values of susceptibility are presented in this figure for each of the strategies. These parameters are the Norway spruce dominated area with stem diameters 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

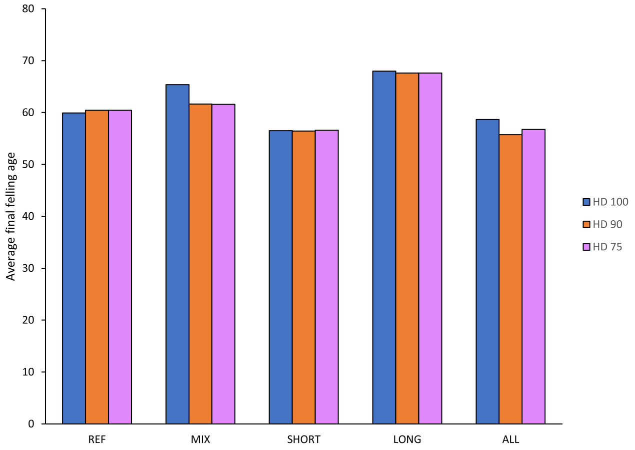

Fig. 8. Average final felling age for harvest demands (HD) 75, 90 and 100%, and for different forest management strategies. HD 100, HD 90, and HD 75 refer to harvest demands 100%, 90%, and 75%, respectively. HD 100 corresponds to the maximum achievable harvest volume subject to an even-flow constraint.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

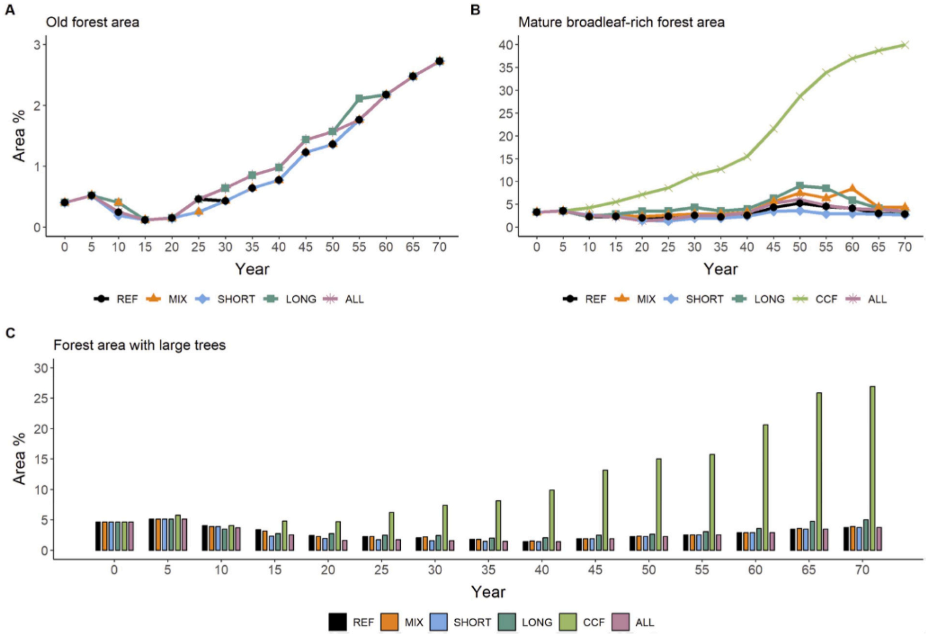

Fig. 9. Biodiversity indicators (related to the Swedish environmental quality objective Living Forests) development over the 70-year planning horizon for harvest demand 90%, A) old forest area, B) mature broadleaf-rich forest area, C) forest area with large trees of conifers and deciduous trees (stem 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.

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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,

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

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

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

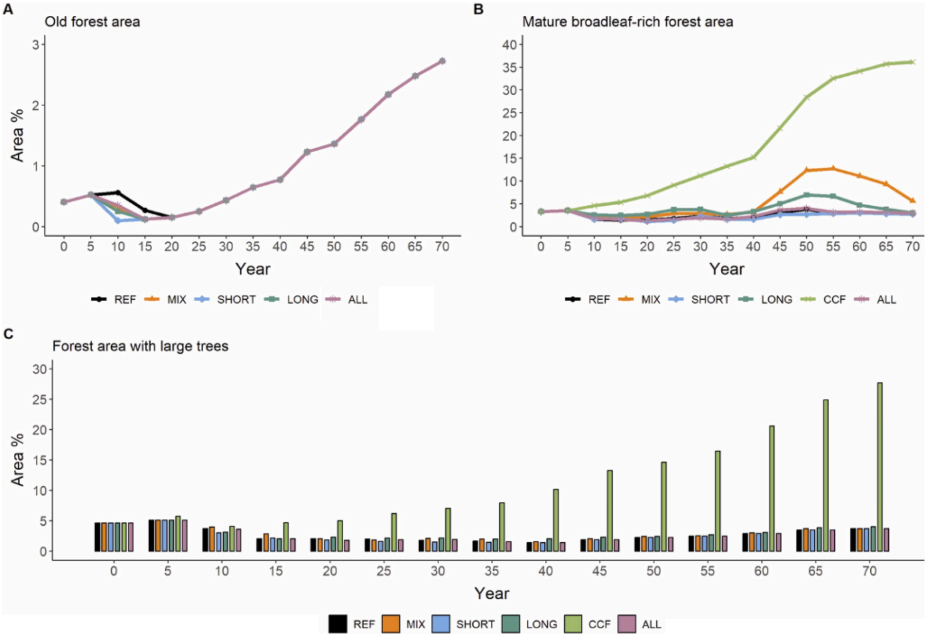
$$\sum_{j=1}^{J_i} x_{ij} = 1 \quad \forall i \in I \tag{B5}$$

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

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



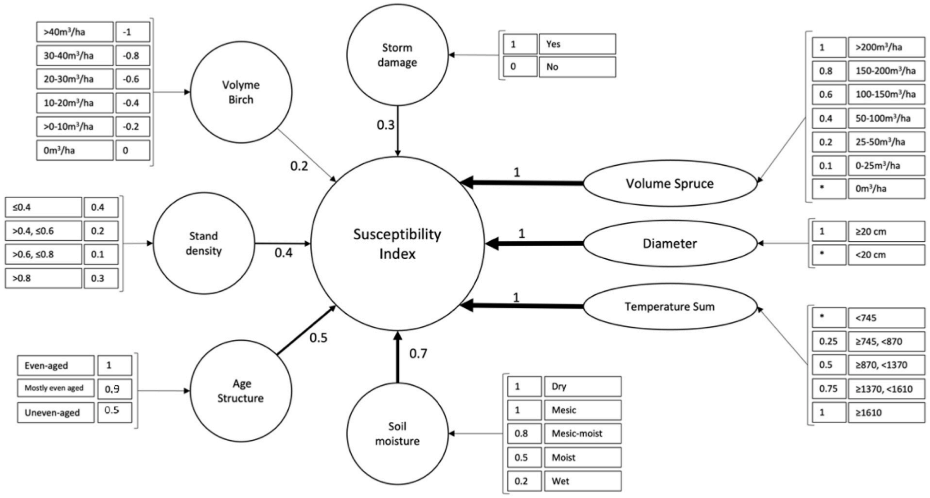
Development of biodiversity indicators over the planning horizon for harvest demand 100%, A) old forest area, B) mature broadleaf forest area, and C) average number of large trees of conifers and deciduous trees. See Table 1 for a detailed description of the management strategies.

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.

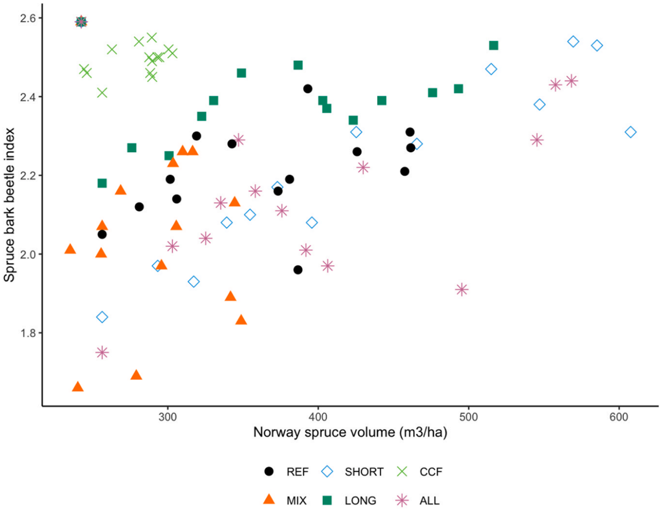
Harvest demand (%)	Management strategy	Year period	Mean age (yr)	Norway spruce stem density (st/ha)	Closure	Mean SBB index
-	-	0	36	1704	0.6	0.86
100	REF	1 – 70	36	2027	0.8	0.94
100	MIX	1 – 70	38	1511	0.7	1.05
100	SHORT	1 – 70	34	2358	0.8	0.76
100	LONG	1 – 70	40	1829	0.8	1.14
100	CCF	1 – 70	-	970	0.7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

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IV

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Spatial optimization for reducing wind exposure of forest stands at the property level

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ABSTRACT

Storms constitute one of the major natural disturbances in Sweden and its associated damages appear to be in an upward trend during the last 35 years in Europe. In addition, storm damages are expected to increase in the future due to the shortening of the soil frost period during the winter caused by climate change. Here we present a new optimization model to be used in forest planning for decreasing the wind exposure for storms over time through the minimization of vulnerable edges between neighbouring stands in a forest property. Three different cases were investigated where height differences of 5, 10 and 15 m between neighbouring stands were used to identify vulnerable edges in the property. The model, which accounts for the higher sensitivity of spruce compared to other tree species, was formulated as a mixed integer programming problem and solved using a branch and bound algorithm in a case study for a forest property in southern Sweden. In the case study, we investigated the trade-off between minimizing the length of vulnerable stand edges and the net present value from wood production. Our results show that it is possible to decrease vulnerable edge length with relatively moderate declines in the maximum achievable net present value, resulting in a clustering of dominant heights of neighbouring stands. Larger decreases in vulnerable edge length led to larger decreases in net present value, and an increased area proportion of forest older than 80 years. This model can easily be adapted to other planning problems in which edge effects are important.

1. Introduction

Forests are subject to a wide range of natural disturbances over their lifetime. In Europe, natural disturbances have accounted for large economic losses during the last 150 years (Schelhaas et al., 2003). Storms alone were responsible for half of this damage, resulting in approximately 17.5 million m^3 of annual timber losses (Schelhaas et al., 2003), with an upward trend during the last 35 years in Europe (Senf & Seidl 2021). In Sweden, storms have harmed more than 100 million m^3 of timber during the last century (Nilsson et al., 2004). In 2005, 75 million m^3 were felled by only one storm in southern Sweden (Holmberg, 2005). In addition, the damage caused by storms is expected to increase in the future due to global warming and the shortening of the soil frost period during the winter because of warmer temperatures (Schlyter et al. 2006; Lindner et al. 2010; Gregow et al. 2011).

Common factors that have a large influence on the forests' sensitivity to storms include tree properties, forest stand characteristics, silvicultural practices and the spatial layout of management activities (Persson 1975; Peltola et al. 1999; Blennow & Sallnäs 2004; Zeng et al. 2007; Hanewinkel et al. 2011; Albrecht et al. 2012; Gardiner et al. 2013; Dhubháin & Farrelly 2018; Venäläinen et al. 2020). Concerning tree properties, tree species can affect the disposition of forest stands to be damaged in the long term (Albrecht et al. 2012). Conifers, in general, are susceptible to storm damage since they keep the needles during late autumn and winter when most storms occur (Schmidt et al. 2010; Gardiner et al. 2013) and spruce in particular, due to the deficiency of rooting depth (Quine & Gardiner 2007). Apart from tree species, tree height also plays a fundamental role, where the damage probability increases greatly with larger heights. In previous studies, forest stands have been classified as 'windstorm sensitive' if dominant heights were over 10 m (Zeng et al. 2007) or 15 m (Lagergren et al., 2012). In addition, forest management activities such as final fellings or thinnings can increase wind exposure and cause a sudden and temporal loss of stability in the forest (Zeng et al. 2006; Wallentin & Nilsson 2014). Forest stands located close to gaps or recently harvested stands, where wind speeds tend to increase and the remaining forest has less stability, are more

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susceptible to suffer damages from strong wind gusts (Zeng et al., 2004).

One way to decrease the risk of storm damage is to formulate optimization problems that integrate the risk of storm damage in the forest planning process (e.g. Meilby et al. 2001; Zeng et al. 2007; Heinonen et al. 2009; Hanewinkel et al. 2010; Ross & Tóth 2016; Zubizarreta-Gerendiain et al. 2017). Forest planning problems that have considered the risk of storm damage have in many cases used heuristic methods for solving the resulting optimization models-(e.g. Lockwood & Moore 1993; Meilby et al. 2001; Zeng et al. 2007). Zeng et al. (2007) investigated how the spatial distribution of clearcuts and the economic gains from the forest were affected by the aggregation of new clearcuts and the avoidance of harvestings close to 'windstorm sensitive' stands. In their study, three heuristic approaches, simulated annealing, tabu search and genetic algorithms were tested. Heinonen et al. (2009) and Zubizarreta-Gerendiain et al. (2017) also focused on minimizing the risk at stand level by using simulated annealing. However, one of the main drawbacks of heuristic methods is that these are not able to find, in most cases, the optimal solution to the planning problem presented.

An alternative to solving planning problems with heuristic techniques is to use exact solution techniques, such as integer programming (IP) with a branch and bound algorithm (Williams, 1985). IP has been used in many forest scheduling problems (e.g. Goycoolea et al. 2005; Constantino et al. 2008) and numerous decision support systems for forest planning are currently based on these kinds of solution methods, e.g. the Heureka system developed and used in Sweden (Wikström et al. 2011). Exact methods have, for example, been implemented as an alternative to heuristics when considering spatial relationships such as edge effects into long-term forest planning for biodiversity purposes. Among others, Öhman & Wikström (2008) investigated how to maximize the NPV over time and at the same time support the spatial clustering of old forest areas to preserve biodiversity by using a mixed integer programming approach. In addition, other spatial problems such as maximum final felling area restrictions, the ecological assemblage of habitats or the production of new forest edges connected to final fellings and their impacts on wildlife habitats have been solved by using exact methods (e.g. Goycoolea et al. 2005; Öhman et al. 2011; Ross & Tóth 2016). Nevertheless, there are so far few model formulations to handle the risk for storm damage solvable with exact solution methods in acceptable solution times and for large forest properties.

The objective of this study is to present and evaluate a model for considering the risk of storm damage in long-term forest planning. The model minimizes the length of forest stand edges that are affected from edge effects from neighbouring stands (forest stands next to each other with common edges) to decrease the risk of storm damage over time and within a forest property. The model can be used in decision support systems using exact solution methods for solving the optimization problem. The planning problem was solved by optimising the spatio-temporal arrangement of forest management activities over the planning horizon within a forest property in southern Sweden. In contrast to previous studies, we have used a longer planning horizon (70 years), a larger study area (538 stands) and a exact method to solve the specified model.

2. Materials and methods

2.1. Modelling framework

The approach for including consideration to wind damage is included in a long-term forest planning problem consisting of selecting forest management activities for every stand in a landscape over time so that the amount of forest stand edges with large height differences between neighbouring stands and dominated by spruce is minimized. The aim was to create a smoother landscape in terms of tree heights between neighbouring stands over the planning horizon. The objective of minimizing the length of edges with large height differences between neighbouring stands is subject to a demand for a net present value and to an even flow timber harvest constraint. As can be seen in the formulation below, the problem formulation is built on the concept of a treatment schedule, which is a sequence of forest management activities over the planning horizon for one single forest stand. Consequently, this problem formulation is building on a model I type formulation (Johnson & Scheurman 1977).

2.2. Model formulation

The mathematical formulation for this forest planning problem is as follows:

$$MinY_1 = \sum_{i=1}^{I} \sum_{l=1}^{L_i} b_{il} \sum_{p=1}^{P} Z_{ilp} \tag{1}$$

Subject to the following constraints:

$$\sum_{j=1}^{J_l} h_{ljp}x_{ij} - \sum_{j=1}^{J_i} h_{ijp}x_{ij} \leq d + MZ_{ilp} \forall p \in P, \forall il \in Y, \forall i \in S \tag{2}$$

$$Z_{ilp} = \{0,1\} \quad \forall il \in Y, \forall i \in S, \forall p \in P \tag{3}$$

$$\sum\nolimits_{i=1}^{I} \sum\nolimits_{j=1}^{J_i} v_{ij(p+1)}x_{ij}a_i \geq (1-\mu) \sum\nolimits_{i=1}^{I} \sum\nolimits_{j=1}^{J_i} v_{ijp}x_{ij}a_i \quad \forall p \in P-1 \tag{4}$$

$$\sum\nolimits_{i=1}^{I} \sum\nolimits_{j=1}^{J_i} v_{ij(p+1)}x_{ij}a_i \leq (1+\mu) \sum\nolimits_{i=1}^{I} \sum\nolimits_{j=1}^{J_i} v_{ijp}x_{ij}a_i \quad \forall p \in P-1 \tag{5}$$

$$\sum\nolimits_{i=1}^{I} \sum\nolimits_{j=1}^{J_i} a_i n_{ij} x_{ij} \geq \beta^* MaxNPV \tag{6}$$

$$\sum\nolimits_{j=1}^{J_i} x_{ij} = 1 \quad \forall i \in I \tag{7}$$

$$x_{ij} = \{0,1\} \quad \forall i \in I, \forall j \in Ji \tag{8}$$

where
i specifies a stand containded in set I,
l specifies a stand neighbour to i contained in set L_i,
j specifies a treatment schedule contained in set J_i,
p specifies a period contained in set P,
I the set of stands,
Y the set of neighbour stands,
S the set of stands with Norway spruce as dominant species,
L_i the set of neighbours to stand i,
J_i the set of treatment schedules for stand i,
J_l the set of treatment schedules for stand l,
x_{ij} the binary decision variable that ensures that stand i is designated the value 1 if treatment schedule j is assigned to stand i,

Z_{ilp} the indicator variable that alternatively takes the value of 1 if the common edge between stand i and l makes up a vulnerable edge in period p, otherwise 0. If vulnerable or not is dependent on d and if the stand is dominated by Norway spruce or not.

d the maximum accepted height difference between two neighbouring stands in order to not consider the common edge between two stands as vulnerable,

v_{ijp} the volume harvested per hectare for stand i and treatment schedule j in period p,

h_{ijp} the height for stand i and treatment schedule j in period p,

h_{ljp} the height for stand l and treatment schedule j in period p,

b_{il} the common edge length between stand i and stand l,

n_{ij} the net present value per hectare for a treatment schedule j and stand i,

M a large number greater than the maximum possible height of a forest stand,

a_i the stand area,

β indicates the percentage of MaxNPV that is demanded,

μ indicates the maximum and minimum harvest deviation allowed between period p and $p+1$,

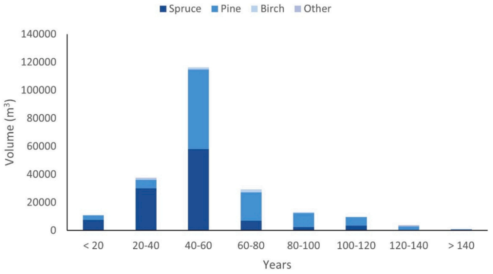

Fig. 1. Initial volume distribution by age class.

MaxNPV is a parameter obtained from maximizing the net present value subject to even-flow harvest constraints (see Appendix A for the mathematical formulation of how *MaxNPV* was calculated).

Eq. (1) minimizes the edge length between neighbouring stands in the forest property if the height difference between them is larger than parameter d. Eqs. (2) and (3) ensure that the indicator variable, Z_{ilp}, takes the value of 1 if the difference in height between two neighbouring stands is larger than the specified value of parameter d and value 0 otherwise. It also ensures that only forest stands dominated by Norway spruce are selected to minimize their vulnerable edges if the conditions in Eqs. (2) and (3) are fulfilled. There is one Eq. (2) for every stand and neighbour, i.e., if one stand has four neighbours there are four Eq. (2) in every period. Eqs. (4) and (5) ensure that the demand for even flow timber harvest is fulfilled. Eq. (6) ensures that we meet the net present value demand. Eqs. (7) and (8) ensure that only one treatment schedule is assigned to each treatment unit.

2.3. Case study

The proposed model was evaluated for a case study area consisting of 538 forest stands encompassing different types of measurements from trees, soil, and site characteristics for each stand such as the productive area, proportion of species or site index, among others. The forest property is located in Småland, Southern Sweden (56°37′N, 15°30′E) and the data was collected during the year 2019. The average stand size is approximately 3.5 ha and in total 1917 ha of productive forest (forest with a mean annual increment greater than 1 $m^3ha^{-1}year^{-1}$) were included in the study. The species distribution was dominated by pine with 48% of the total volume and by spruce with 45% (Fig. 1). In addition, 95% of the forest property area was managed for timber production and 5% of the productive forest was set aside for nature conservation purposes. The forest planning horizon for this study was 70 years divided into 14 five-year periods.

The simulation of treatment schedules including future forest conditions was done using the Heureka PlanWise system (version 2.17.2.0) (Wikström et al. 2011). PlanWise simulates the development of the tree layer based on empirical single-tree models and height functions in time steps of five years. The regression models used to simulate the development of the forest are based on the National Forest Inventory, the HUGIN young stand survey and scientific trials (Wikberg 2004; Fahlvik et al. 2014). PlanWise offers the user the possibility to select different management systems (even-aged, uneven-aged, and unmanaged) and modify the settings for silvicultural practices including regeneration, cleaning, thinning, final felling and fertilization, among others. The settings for final fellings follow the Swedish Forestry Act (SFS 1979).

In the case study, a set of potential treatment schedules based on four different management strategies was generated for every forest stand. The four management strategies were the following:

- Default management strategy defined in PlanWise (production), but the final felling age was delayed by 0 – 20 years;
- As production, but the final felling age was delayed by 20 – 45 years;
- As production, but the final felling age was delayed by 45 – 70 years;
- No management.

The forest areas in the stand register that were identified to have high nature conservation values were designated to the “No management” strategy. The identification of these areas was done based on different forest conditions such as volume of dead wood or proportion of deciduous trees. All four strategies were applied to the rest of the stands in the forest property. The maximum final felling delay allowed for more flexibility when selecting the best treatment schedule alternative in the optimization. A discount rate of 2.5% was chosen for the calculations of discounted costs and revenues of harvest and silvicultural practices. The calculations were done in Swedish crowns (SEK) and the results presented in Euros (EUR), where 10 SEK = 1 EUR. For the forest development simulation, on average twelve potential treatment schedules were generated for each stand over 14 five-year periods.

The mixed integer programming problem was formulated using Heureka’s optimization module utilizing Zimpl (Koch 2005) and Gurobi 8.1 as a solver using a branch and bound algorithm approach. The total number of variables and constraints was between 41,000 and 58,000. The computer used had a 2.40 GHz Intel® Core™ i9-9980HK processor. A relative mip gap of 0.01% was used meaning that once the solver found an integer solution within 0.01% of optimal this solution was declared optimal. The final mip gap was below 0.01 for all cases and alternatives. The stated planning problem was solved for three different cases with d values of: 5, 10 and 15 m. In this study, stand *i1* was considered to create an edge effect into stand *i2* if the height difference between stands *i1* and *i2* was more than the specified value of d (see equation (2)). d is the maximum height difference value, in meters, allowed between two stands under which no edge effect is considered to occur. The choice of larger values of d implied the identification of less vulnerable edges compared to smaller and more restrictive values such as 5 m. To analyse the trade-off between NPV and the total vulnerable edge length (VEL), the optimization problem was solved 9 times for each d value with the following increasing NPV demand alternatives in % (equation (6)): 70, 80, 90, 95, 96, 97, 98, 99 and 100, and with even-flow harvest constraints. The NPV demand alternatives are hereafter denoted NPV70, NPV80 and so forth. The maximum NPV corresponds to NPV100 (see Appendix A). The even-flow harvest constraints (equation (4) and (5)) permitted a maximum harvest increase or decrease of 20% from period to period. This was done to investigate the impact of both net present value and even-flow harvest constraints on the total vulnerable edge length in the forest property.

To determine if the optimization model was able to create a landscape with similar heights between neighbouring stands we used the Global Moran I (GMI) correlation coefficient to assess whether or not the resulting dominant heights within the forest property had a clustered, random or dispersed pattern (Getis & Ord 1992). The GMI statistical test gives a measure of spatial autocorrelation for the entire forest property. This meant that if a clustered pattern was identified, forest stands located next to each other in the forest property tended to have similar dominant height values which would, in turn, meet the objective of the optimization model. The GMI value was calculated every two periods, namely eight times during the planning horizon (periods 0, 2, 4, 6, 8, 10, 12 and 14) to assess the development of the spatial autocorrelation for all d cases. In these estimations, only forest stands with common edges were used in the calculations. Case $d = 10$ was chosen for the calculations since in previous studies forest stands with dominant heights of at least 10 m were identified as “windstorm sensitive” e.g. Zeng et al. 2007.

3. Results

The model was solved for three different d cases and nine different

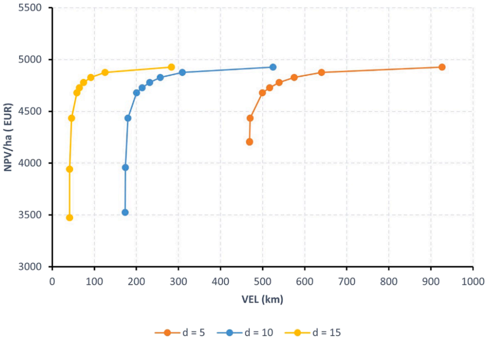

Fig. 2. Trade-off curve between net present value (NPV) and total vulnerable edge length (VEL) over the planning horizon for the investigated cases ($d = 5$, $d = 10$, $d = 15$). The points on each curve from the right to the left NPV100, NPV99, NPV98, NPV97, NPV96, NPV95, NPV90, NPV80 and NPV70. In curve $d = 5$, NPV80 and NPV70 have similar values and overlap in the figure.

NPV demand alternatives. An even flow harvest constraint was applied for all cases and alternatives and the solution times are presented in Appendix C. Table C.2.

The total VEL over the planning horizon varied between 41 and 927 km among the different *d* cases and NPV demand alternatives (Fig. 2). Small declines on the maximum NPV, 1–5%, were able to produce large decreases of VEL for all cases. A decrease of 1% of the NPV demand from the maximum NPV resulted in a decrease of 31, 41 and 56% for *d* cases 5, 10 and 15, respectively. In addition, a decrease of 5% in NPV demand resulted in a lowering of VEL by 46, 62, and 79% for *d* values of 5, 10 and 15. Further declines, down to NPV90 and below, occured simultaneously with an abrupt decline in the NPV. For case $d = 10$, NPV99 and NPV90 resulted in a reduction of the maximum VEL of 41 and 65%, respectively, compared to NPV100 (Fig. 2). However, for this case only small vulnerable edge declines of <6.5 km were achieved when reducing the NPV demand further from NPV90 down to NPV70. The largest reduction of VEL was achieved in case $d = 15$ where the edge decreased by 85% for NPV70 compared with NPV100.

The harvest volume from final fellings was larger for higher NPV demands compared to lower NPV demands during the first half of the planning horizon (Fig. 3, Appendix B.1.). In contrast to this, the harvested volume during the second half of the planning horizon varied more among NPV alternatives. NPV80 and NPV70 presented the lowest harvested volumes throughout the whole planning horizon. On the other hand, the total volume harvested from thinnings was quite similar for NPV100, NPV95 and NPV90 during the first 45 years (first 9 periods) (Fig. 3). However, in the last 25 years (periods 10 to 14) of the planning horizon the differences became larger and in comparison to NPV100, the harvested volume from final fellings and thinnings was 16 and 26% lower for NPV95 and NPV90, respectively. NPV80 and NPV70 showed considerably lower harvested volumes after 70 years ending up being 20 and 35% lower than NPV100, respectively.

The amount of forest area older than 80 years increased progressively over the planning horizon for case $d = 10$ with decreasing NPV demand (Fig. 4). NPV100 presented in total 6% of the total forest area above this age. NPV95 and NPV90 showed a considerable gain of forest over 80 years old with 11 and 19% of the total area respectively, compared to NPV100. In addition, NPV80 and NPV70 presented the largest increases with more than 33 and 40% respectively.

The initial period, common for all cases and NPV demand alternatives, for which the GMI was calculated showed a GMI value of 0.079 (p-value < 0.01; z-score: 3.00) (Appendix C) suggesting a strong clustered pattern. This meant that, for the initial period, neighbouring forest stands tended to have similar dominant height values. In the NPV95 alternative, all the investigated periods presented clustered patterns with<1% likelihood (p-value < 0.01) suggesting that the patterns had $<$1% probability of being the result of a random chance. For this alternative, the GMI value increased considerably over time up to period 8, when it started decreasing again for all three cases (Fig. 6, Appendix C.1.). Including the model demand in the optimization resulted in clustered patterns over time for all cases and NPV demand alternatives, compared to alternative NPV100 which didn't include this demand (Fig. 5, Appendix B.2.). In contrast, for the NPV100 alternative, the GMI value hardly changed over time meaning that different values of *d* didn't generate large differences on the index over the planning horizon. This alternative developed regular random patterns even if some occasional clustered patterns ocurred in the middle of the planning horizon.

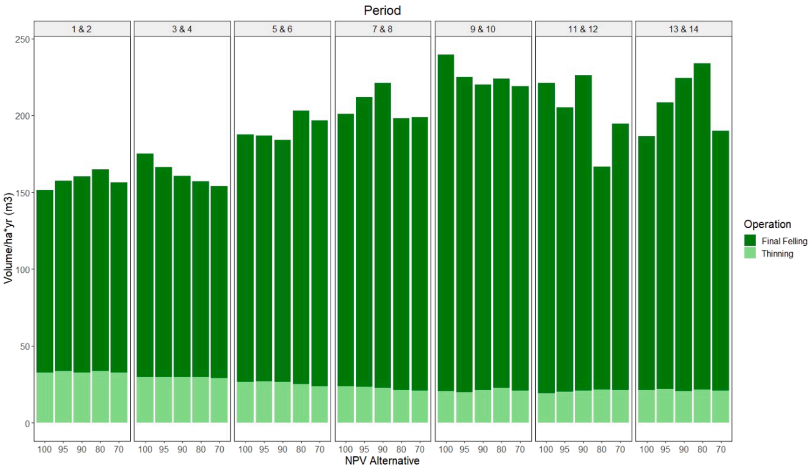

Fig. 3. Harvest profile for case $d = 10$ and NPV alternatives NPV100, NPV95, NPV90, NPV80 and NPV70. The harvest profile was calculated for all periods grouped two by two where each group represents a ten-year period.

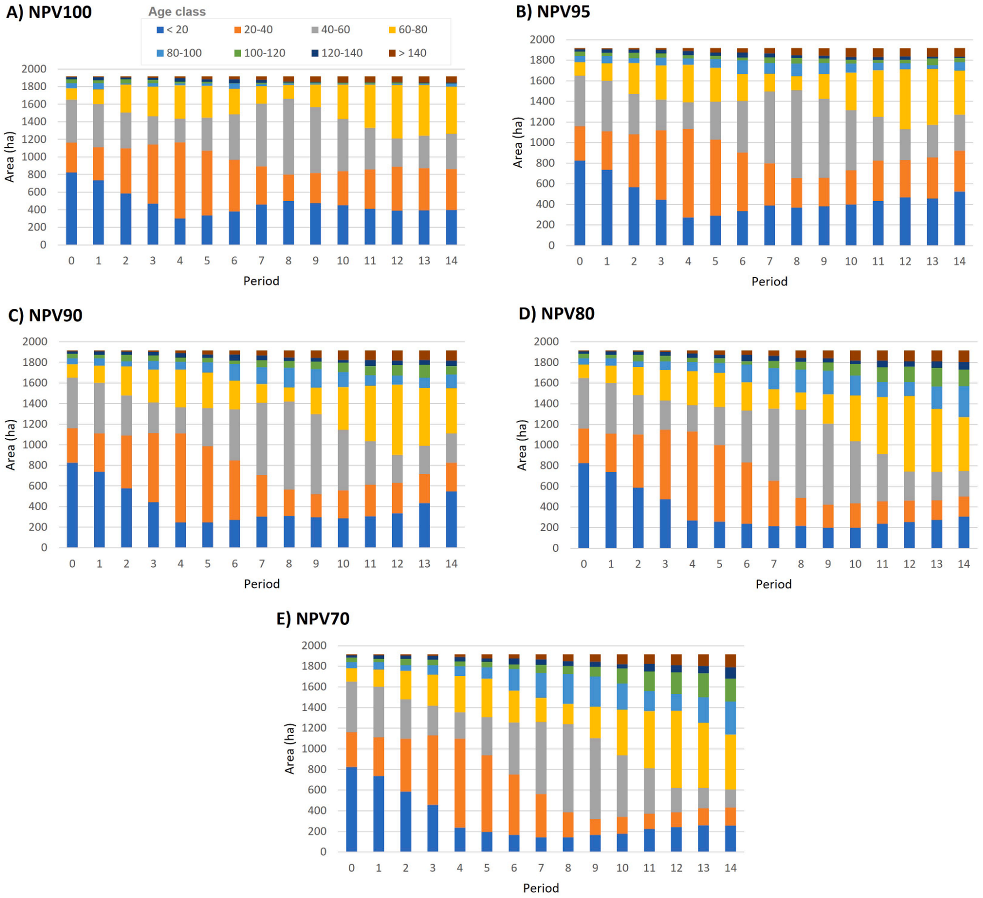

Fig. 4. Area distribution by age class and per period. For case $d = 10$ A) NPV100, B) NPV95, C) NPV90, D) NPV80 and E) NPV70.

4. Discussion

Nowadays, numerous optimization approaches provide the possibility to consider spatial relationships at large scales in order to solve complex problems with several simultaneous objectives. Here we presented a model to reduce height differences between neighbouring stands over time to reduce the overall wind exposure by using mixed integer programming together with a traditional branch and bound algoritm as exact solution technique.

The proposed model demonstrated a large potential to minimize the number of vulnerable edges affected from edge effects over time and within the forest property. However, large reductions on the VEL were only achieved for already relatively moderate declines of NPV regardless of which d value was used. The wind exposure of forest stands at the property level decreased over time when the height differences between stands with common edges was minimized. The resulting forest landscape was smoother regarding dominant heights at the end of the planning horizon and goes in line with results obtained from similar studies where, in turn, heuristic methods were applied (Zeng et al. 2007; Heinonen et al. 2009; Zubizarreta-Gerendiain et al. 2017).

The results indicate that the choice of the maximum height difference allowed between neighbouring stands to consider a forest stand edge vulnerable or not had a substantial impact on the identification of vulnerable edges in the property and their minimization. Applying larger values of maximum height differences between stands decreased the total VEL identified to a great extent. Despite this, the GMI values obtained for the largest d value investigated, $d = 15$, also showed strong clustered patterns with high values as well as for cases $d = 5$ and $d = 10$. Apart from this, the reduction of the VEL of the property influenced the spatiotemporal distribution of final fellings where the model was prone to delay and cluster some of them. This result is in line with the finding that was previously observed by Zeng et al (2007) where the

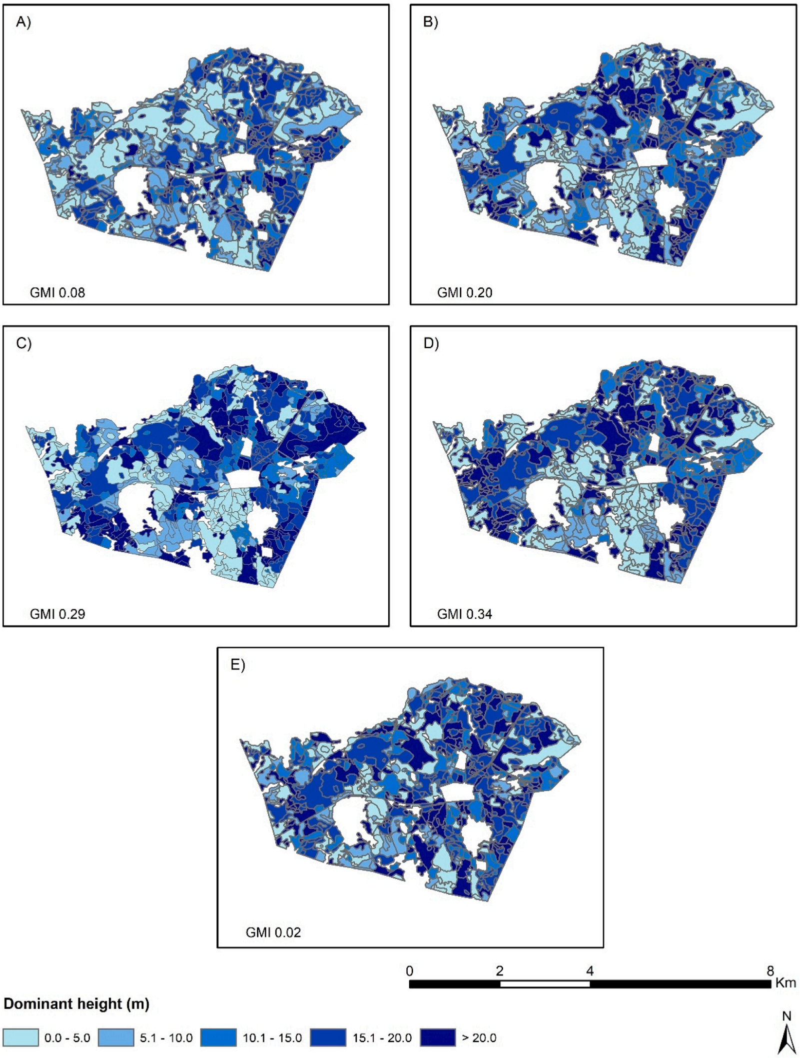

Fig. 5. Distribution of dominant heights and the Global Moran Index value in the initial period 0 (A) and in the final period 14 for NPV95; case $d = 5$ (B), case $d = 10$ (C), case $d = 15$ (D) and for NPV100 and case $d = 10$ (E). NPV100 for the three different d cases displayed similar values and therefore only $d = 10$ was presented in the figure.

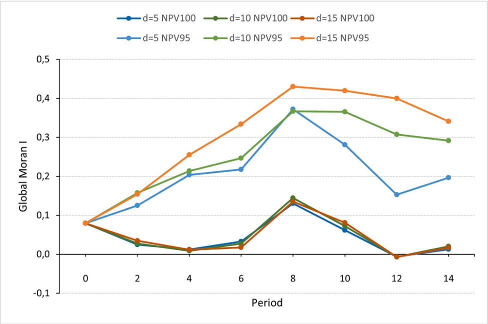

Fig. 6. Global Moran I autocorrelation analyses for cases $d = 5$, $d = 10$ and $d = 15$, and NPV demand alternatives NPV100 and NPV95. In alternative NPV95, all GMI values were statistically significant with $p < 0.01$. In alternative NPV100, periods 8 and 10 were statistically significant with $p < 0.05$ and a random pattern was present in the rest of the periods.

minimization of the occurrence of forest edges identified as vulnerable lead to the clustering of final fellings areas. In addition, the delay of final fellings led to an increase in the amount of forest area over 80 years old which ended up being up to 40% of the whole property when decreasing largely the NPV demand down to NPV70 and for case $d = 10$.

The resulting trade-off curve showed nine different combinations of NPV demand alternatives and their corresponding VEL. It was possible to decrease the amount of VEL rapidly for NPV demand alternatives down to NPV95, and after this point substantial NPV decreases were needed to continue reducing the VEL. This finding can provide adequate support and flexibility to different types of decision makers according to their risk aversion. Decision-makers who are more risk-averse should choose solutions that are further to the right of the trade-off curve.

On the other hand, NPV100 alternative also presented sporadical clustered patterns in the forest property without applying any demand to minimize the VEL. These clustered patterns appeared at periods 8 and 10 and could possibly be explained by the initial state of the forest which already displayed a clustered pattern and after an entire rotation period similar structures to the initial one may be developed. Nevertheless, in our study the production of more even landscapes regarding dominant heights led to a particularly high increase in the proportion of forest over 80 years old in the property for NPV80 and NPV70. This suggests that when NPV demands are considerably reduced the need to harvest disappears to a large extent and the harvest levels decrease leaving older forest stands in the landscape. Nonetheless, this had nearly no impact on the average final felling age for any case or NPV demand alternative. One reason that could explain this is that in alternatives NPV70 and NPV80 a larger proportion of forest is left uncut resulting in two different situations. First, the average stand age of the property gets gradually older, and second, the remaining logged forest for these alternatives continues to be harvested at similar ages compared to NPV95, for example.

When dealing with different types of risks or natural disturbances, the use of operations research techniques is convenient as they provide the possibility of integrating spatial considerations into forest planning. Previous planning problems dealing with the risk of storm damage have mostly been solved utilising different heuristic techniques (Meilby et al. 2001; Zeng et al. 2007; Zubizarreta-Gerendiain et al. 2017) and only a few using exact methods (e.g. Ross & Tóth 2016). The latter ones have been more often implemented when taking into account ecological and biodiversity conservation goals (e.g. Bettinger et al. 2003; Öhman & Wikström 2008) and seldom when considering the risk of storm damage in the forest planning process. Some of the most common heuristic techniques applied in planning problems have been simulated annealing, tabu search and genetic algorithms. However, these cannot ensure that the optimal solution is found. This study has successfully implemented exact methods using a branch and bound algorithm, which in turn makes this model easier to use by forest companies or forest owners as many decision support systems (DSS) are built on exact methods.

Although the model can easily be adapted to other planning problems if adequate input data is available and by changing the decision variable, it does not include all aspects of relevance to storm damage. For example, specific considerations connected to forest management activities that could cause a loss of stability in the forest, such as thinnings or other management activities involving the removal of timber, were not included. For this reason, the addition of constraints to limit these activities, to some extent, to prevent from increasing the probability of damage to older stands could be considered. Moreover, and as long as it is not in conflict with nature conservation objectives, restrictions can be added to minimize the creation of forest areas that could be more susceptible to strong wind gusts i.e., old forest stands or stands with great heights. On the other hand, priorities could be set to reduce the VEL of forest stands depending on their location in the property and in relation to the winds' prevailing direction. Forest stands located upwind, from where the wind is coming, are more exposed to strong winds and therefore have a higher risk of suffering wind damage. Hence, these could be prioritized over the rest.

5. Conclusion

Overall, the model performance was successful and the VEL were reduced substantially over time with only small NPV declines. The trade-off curve exemplified the risk degree for all alternatives and cases being a good means for forest owners or managers to support decisions based on their risk aversion.

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CRediT authorship contribution statement

Teresa López-Andújar Fustel: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Jeannette Eggers:** Conceptualization, Methodology, Writing – original draft, Supervision. **Tomas Lämås:** Conceptualization, Methodology, Writing – original draft, Supervision. **Karin Öhman:** Conceptualization, Methodology, Writing – original draft, Supervision.

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

Mathematical formulation for the Maximum Net Present Value (MaxNPV).

$$MaxNPV = \sum_{i}^{I} a_i \sum_{j}^{J} d_{ij}x_{ij} \tag{A.1}$$

Subject to:

$$\sum_{i=1}^{I}\sum_{j=1}^{J_i} v_{ij(p+1)}x_{ij}a_i \geq (1-\mu)\sum_{i=1}^{I}\sum_{j=1}^{J_i} v_{ijp}x_{ij}a_i\forall p \in P-1 \tag{A.2}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J_i} v_{ij(p+1)}x_{ij}a_i \leq (1+\mu)\sum_{i=1}^{I}\sum_{j=1}^{J_i} v_{ijp}x_{ij}a_i\forall p \in P-1 \tag{A.3}$$

$$\sum_{j=1}^{J_i} x_{ij} = 1\forall i \in I \tag{A.4}$$

$$x_{ij} = \{0,1\}\forall i \in I, \forall j \in Ji \tag{A.5}$$

where:

x_{ij} is the binary decision variable that ensures that stand i is designated the value 1 if treatment schedule j is assigned to stand i,

v_{ijp} is the volume harvested for stand i and treatment schedule j in period p,

μ indicates the maximum and minimum harvest deviation allowed between period p and $p + 1$.

a_i is the area in hectares of stand i,

d_{ij} is the NPV per hectare of stand i and treatment schedule j from period 1 to infinity,

Equation (A.1) is the objective function, i.e. summarizes the net present value of all stands and their corresponding treatment schedules. Equations (A.2) and (A.3) ensure that the maximum fluctuation of timber harvest per period is fulfilled. Equations (A.4) and (A.5) ensure that only one treatment schedule is assigned to each treatment unit.

Appendix B

See Figs. B1 and B2

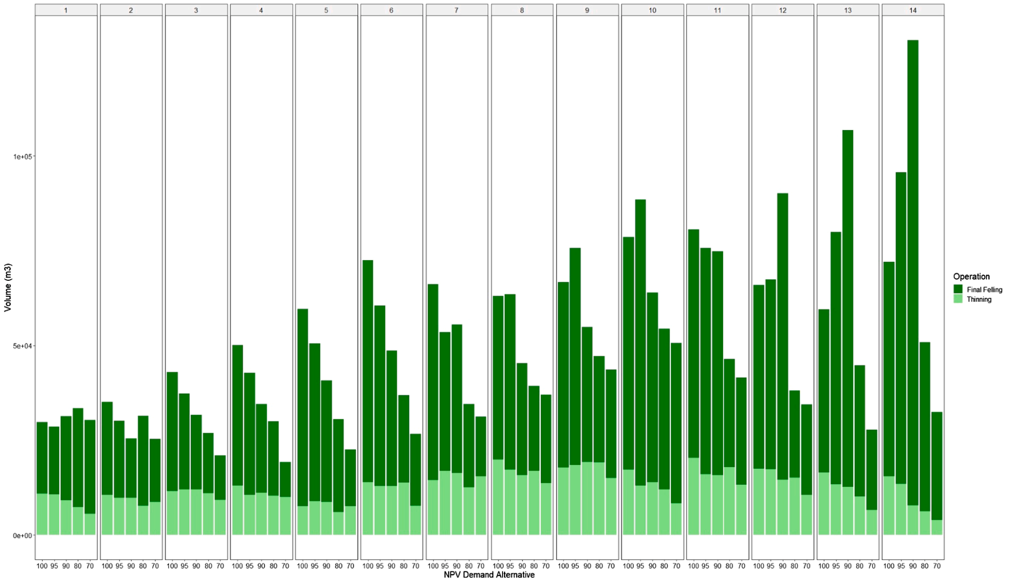

Fig. B1. Harvest profile. Estimations for case $d = 10$ and all periods in the planning horizon (five-year periods). NPV100, NPV95, NPV90, NPV80 and NPV70 were included.

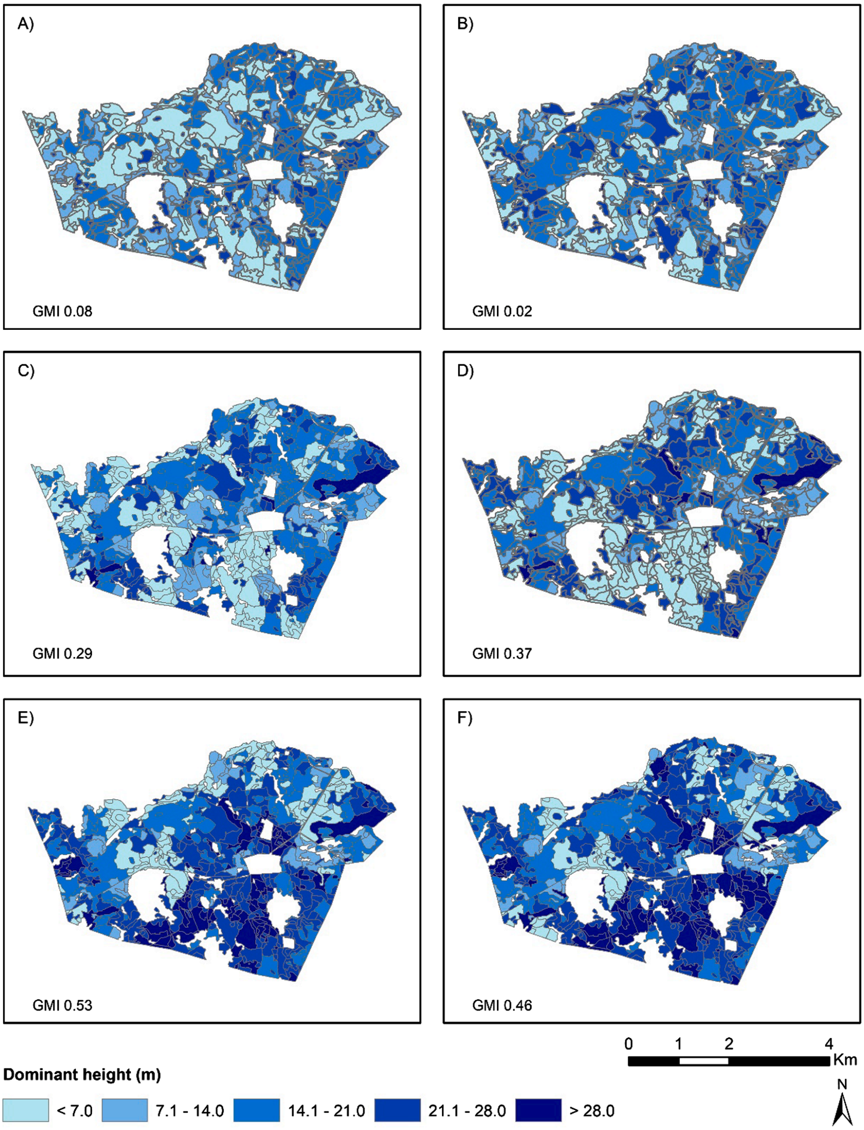

Fig. B2. Dominant height distribution for case $d = 10$ and different NPV alternatives in A) the initial period 0; B) NPV100 and period 14; C) NPV95 and period 14; D) NPV90 and period 14; E) NPV80 and period 14; F) NPV70 and period 14.

Appendix C

See Tables C1 and C2

Table C1
Global Moran I statistical test calculations. The Global Moran I (GMI) value, p-value and z-score are presented for all cases, alternatives NPV100 and NPV95 and every two periods. (i) common period for all cases and NPV alternatives.

d Case	NPV Alternative	Period	GMI Value	p-value	z-score
5	100	0 (i)	0,079449	0,002634	3,007464
	100	2	0,024985	0,320689	0,993042
	100	4	0,012430	0,597095	0,528583
	100	6	0,032960	0,197848	1,287707
	100	8	0,130594	0,000001	4,898667
	100	10	0,062023	0,018116	2,363230
	100	12	−0,006510	0,863589	−0,171807
	100	14	0,012773	0,588117	0,541567
5	95	2	0,124938	0,000003	4,690196
	95	4	0,203941	0,000000	7,611725
	95	6	0,217457	0,000000	8,111431
	95	8	0,372095	0,000000	13,829924
	95	10	0,280861	0,000000	10,456064
	95	12	0,153039	0,000000	5,728877
	95	14	0,196420	0,000000	7,333770
10	100	2	0,027498	0,277491	1,085973
	100	4	0,008960	0,688938	0,400296
	100	6	0,027388	0,279396	1,081677
	100	8	0,144124	0,000000	5,399025
	100	10	0,072414	0,006004	2,747562
	100	12	−0,007186	0,843979	−0,196807
	100	14	0,020451	0,409012	0,825633
10	95	2	0,157379	0,000000	5,890312
	95	4	0,213806	0,000000	7,976411
	95	6	0,246881	0,000000	9,199224
	95	8	0,367011	0,000000	13,641735
	95	10	0,365361	0,000000	13,581718
	95	12	0,307339	0,000000	11,436457
	95	14	0,291464	0,000000	10,848762
15	100	2	0,034542	0,178150	1,346472
	100	4	0,011694	0,616096	0,501391
	100	6	0,017700	0,469400	0,723456
	100	8	0,134968	0,000000	5,060457
	100	10	0,081092	0,002151	3,068533
	100	12	−0,006717	0,857563	−0,179477
	100	14	0,017074	0,483485	0,700708
15	95	2	0,154467	0,000000	5,782022
	95	4	0,254940	0,000000	9,496632
	95	6	0,333894	0,000000	12,416754
	95	8	0,429820	0,000000	15,965173
	95	10	0,419705	0,000000	15,592241
	95	12	0,399973	0,000000	14,863943
	95	14	0,341067	0,000000	12,683807

Table C2
Processing time. The solution times and vulnerable edge length (VEL) for the studied *d* cases ($d = 5$, $d = 10$, $d = 15$) and NPV alternatives (NPV100, NPV99, NPV98, NPV97, NPV96, NPV95, NPV90, NPV80 and NPV70) is presented.

d Case	NPV Alternative	VEL (%)	Solution Time (s)
5	NPV100	0.0	667
	NPV99	−31.1	663
	NPV98	−38.1	1012
	NPV97	−42.0	614
	NPV96	−44.4	1907
	NPV95	−46.2	560
	NPV90	−49.4	916
	NPV80	−49.6	2485
	NPV70	−49.6	530
10	NPV100	0.0	6761
	NPV99	−41.1	368
	NPV98	−51.1	259
	NPV97	−55.8	255

(*continued on next page*)

Table C2 (*continued*)

d Case	NPV Alternative	VEL (%)	Solution Time (s)
	NPV96	−59.2	255
	NPV95	−61.8	139
	NPV90	−65.7	51
	NPV80	−66.9	93
	NPV70	−66.9	43
15	NPV100	0.0	2290
	NPV99	−55.6	567
	NPV98	−67.7	114
	NPV97	−73.7	406
	NPV96	−77.3	246
	NPV95	−79.4	351
	NPV90	−83.8	12,300
	NPV80	−85.5	61
	NPV70	−85.5	48

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This thesis increases our understanding of how forest management planning can reduce forest susceptibility to natural disturbances. Well-known management strategies and their influence on the forests' susceptibility to damage are investigated. The thesis also presents new planning models intended to reduce forest susceptibility to damage by European spruce bark beetle and wind. The results suggest that forest planning, backed by sufficiently robust knowledge, is able to target the key forest characteristics to create more resistant forests.

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