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Integrating wind damage vulnerability into long-term forest planning: An optimisation-based model for spatial decision support

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A B S T R A C T

The vulnerability of forests to wind damage depends to a large degree on the characteristics of the specific stand and its neighboring stands, making forest management a key action in modifying the forest's wind damage vulnerability. Thus, by strategically planning where and when different forest management activities are scheduled to happen, forest managers can influence a forest's vulnerability to wind damage. In this study, we present a long-term forest planning model that identifies optimal forest management activities accounting for this specific vulnerability. The main decision in the model concerns the management of each individual stand throughout the planning horizon when the objective is to fulfil traditional long-term forest management goals and also to reduce the vulnerability to wind damage. In the model, consideration of wind damage is included by banning management activities such as final fellings in stands adjacent to highly vulnerable stands. Furthermore, the optimization model applied is specifically structured to be solvable using exact solution techniques. The model is evaluated for a case study area of 2450 hectares in southern Sweden for a 70-year planning horizon. Results suggest that it is possible to incorporate wind damage considerations into a long-term harvest scheduling problem. The proposed model excels in its ability to offer flexibility, allowing users to freely modify the settings in the model to choose their definition of vulnerability to wind damage. In addition, the model can be included in a traditional decision support system for forest planning utilizing exact solution techniques.

Introduction

Traditionally, the objective of long-term forest planning has been to ensure a sustainable harvest of timber and pulpwood over time. This remains a common objective, but it is also necessary to manage and balance other values, such as nature conservation, carbon sequestration, and recreational aspects. Moreover, adaptation to and mitigation of climate change has become increasingly important, affecting optimal forest management. Thus, the complexity of planning has increased, and there is a need for decision support tools that can help decision-makers identify the best possible action plan for reaching forestry objectives. One example of an aspect that forest managers can include in the planning process is the vulnerability of forests to wind damage. Windstorms have been a prominent natural disturbance in Europe during the last decades causing, at times, large timber losses. Two of the most recent and severe storms that have taken place in Sweden during the last years have been the storm events named Gudrun in 2005 and Per in 2007 (SMHI 2021). Both had important economic impacts where >70 and 12 million m^3 of timber were damaged by the storms, respectively (SMHI 2021). The volume felled by the Gudrun storm event was close to today's annual Swedish harvest volume (Nilsson et al., 2022). Even though no large changes in storm frequency and intensity are expected during the rest of this century (SMHI 2021), the vulnerability of boreal forests to be damaged by wind is expected to increase due to the shortening of the frozen soil period impairing the anchorage of trees to the ground (Laapas et al. 2019; Feser et al. 2015; Gregow et al. 2011).

Besides frozen soil, the vulnerability to wind damage depends also on many other factors defined at the tree, stand, and landscape level. Local wind climate is important as regions with high average windspeeds are more likely to suffer from wind damage compared to forest areas where high windspeeds are rare. Different tree species have different vulnerabilities to wind damage due to the canopy and root structure (e.g., Ni Dhubain 2018; Peltola et al., 1999a). In general, conifers tend to be more susceptible to damage from wind than broadleaves. Norway spruce

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Table 1

Mathematical description of the planning problem. Eq. (1) maximizes the net present value (NPV) from future forest management. Eq (2) and (3) ensure that the timber harvest level in each period does not differ by more than a certain percentage from the average harvest level overall planning periods. Eq. (4) ensures that if the total sensitivity index (TSI) in a stand, for a treatment program, and on a specific period is higher than a predefined threshold value, then final felling in any of the adjacent stands (i.e., stands that share a common border) is forbidden. Finally, Eq. (5) and (6) ensure that one and only one treatment program is assigned to each stand.

$$Max\ W = \sum_{i=1}^{I} \sum_{j=1}^{J_i} a_i n_{ij} x_{ij} \quad (1)$$

$$\sum_{i=1}^{I} \sum_{j=1}^{J_i} v_{ijp} a_i x_{ij} \geq (1-\gamma)\left(\sum_{p=1}^{P} \sum_{i=1}^{I} \sum_{j=1}^{J_i} v_{ijp} x_{ij} a_i\right) /P\ \forall p \in P \quad (2)$$

$$\sum_{i=1}^{I} \sum_{j=1}^{J_i} v_{ijp} a_i x_{ij} \leq (1+\mu)\left(\sum_{p=1}^{P} \sum_{i=1}^{I} \sum_{j=1}^{J_i} v_{ijp} x_{ij} a_i\right) /P\ \forall p \in P \quad (3)$$

$$\sum_{j=1}^{J_i} g_{ijp} x_{ij} + \sum_{j=1}^{J_k} m_{kjp} x_{kj} \leq 1\ \forall i \in I,\ \forall k \in K_i, \forall p \in P \quad (4)$$

$$\sum_{j=1}^{J_i} x_{ij} = 1\ \forall i \in I \quad (5)$$

$$x_{ij} = \{0,1\}\ \forall i \in I,\ \forall j \in Ji \quad (6)$$

where:

i	specifies a stand contained in set I,
J	specifies a treatment program contained in set J_i,
K	specifies a stand neighbour to stand i contained in set K_i,
P	specifies a period contained in set P,
I	*is* the set of stands,
J_i	is the set of treatment programs for stand i,
J_k	is the set of treatment programs for stand k,
K_i	is the set of neighbours to stand i, i.e. stands that share border with stand i,
x_{ij}	is the binary decision variable that ensures that stand i is designated the value 1 if treatment program j is assigned to stand i,
v_{ijp}	is the volume harvested per hectare for stand i and treatment program j in period p,
n_{ij}	is the net present value per hectare for treatment program j and stand i,
g_{ijp}	is 1 if treatment program j for stand i in period p causes a TSI larger than the user-defined threshold TSI, otherwise it is 0,
m_{kjp}	is 1 if treatment program j for stand k includes a final harvest in period p,
a_i	is the stand area for stand i,
γ	indicates the maximum decrease in harvest allowed between period p and the average harvest volume over all stands and periods,
μ	indicates the maximum increase in harvest allowed between period p and the average harvest volume over all stands and periods.

(*Picea abies* L.) is one of the most vulnerable conifers regarding wind damage (Peltola et al. 1999b; Jackson et al. 2019). Tree height is another important aspect, i.e., there is a higher probability of wind damage in forest stands with tall trees compared to stands with shorter trees (Gardiner et al. 2013). In addition, increased growth rates due to longer vegetation periods in boreal forests may lead to taller tree heights at younger ages and consequently, an increased probability of wind damage at younger ages (Elfving and Tegnhammar 1996). Other aspects affecting vulnerability to wind damage are e.g., stand density, site characteristics, forest fragmentation at the landscape level, and the sudden removal of timber during thinning and final felling (e.g., Peltola et al. 1999a and Venäläinen et al. 2017).

Since the vulnerability to wind damage depends to a large degree on the characteristics of a specific stand and its surroundings, forest management can impact the forest stand's vulnerability. Thus, damage vulnerability can be reduced by carefully planning where and when different forest management activities are scheduled to happen (e.g., Kellomäki 2017). Any timber removal e.g., a thinning, is likely to cause a temporary decline in the forest's stability that will take several years to fully recover (Ruel, 1995). In particular, thinnings occurring late in the rotation period when trees have reached a certain height can substantially increase the risk of windthrow (Ní Dhubháin and Farrelly, 2018). Forest management also has an important role in shaping the forest structure to reduce the wind load over the canopy and exposure of the tree canopy (e.g., Heinonen et al. 2009). Thus, for a specific stand of mature forest with tall trees, the vulnerability to wind damage increases if final felling or thinning is taking place in the adjacent area.

To effectively account for wind damage in forest management, we must integrate suitable methods and tools into forest planning. Previous studies have investigated the main risk factors associated with wind damage and have developed empirical risk and probability models (e.g., Valinger and Fridman 1997; Scott 2005; Ní Dhubháin et al. 2018). Generally, empirical models use regression analyses to relate the potential damage by the wind on a set of stands with tree attributes, stand characteristics, and other site components as explanatory variables (Scott 2005). Typically, some of the most common variables identified by these models for predicting the risk of wind damage have been wind speed, topography, soil moisture, stand density, dominant tree height, tree attributes (e.g., species, height-diameter ratio, and crown size), rooting depth, and forest management activities (e.g., final fellings, thinnings) (Scott 2005; Scott and Mitchell 2005; Valinger and Fridman 2011; Albrecht et al. 2012; Díaz-Yáñez et al. 2017). On the other hand, mechanistic models have been built to predict critical wind speed (CWS), i.e., if the CWS is exceeded a tree is assumed to be broken or uprooted (e.g., Peltola et al. 1999b, Gardiner et al. 2000). Such a model in combination with wind climate models enables estimates of potential wind damage (Hale et al. 2015). However, even if there are examples of predicting the risk of wind damage and models for critical wind speeds, only a few studies have included the models in long-term forest planning problems for identifying the optimal management plan. One example is a study by Heinonen et al. (2009) in which they calculated CWS and estimated a wind damage risk index using the probability of occurrence of wind speeds exceeding CWSs over the coming 10-year period. The mechanistic model HWIND was used to estimate the CWS (Peltola et al. 1999b) of each forest edge in the study area. Following this, the index was included in the objective function of an optimization model to solve the proposed planning problem. For the optimization, they employed a heuristic method known as simulated annealing. Another example is a study by López-Andújar Fustel et al. (2021), which presented a model for minimizing the length of vulnerable edges between neighbouring stands within a forest property. However, the model considered only edge susceptibility in terms of height differences between adjacent stands and no other forest attributes were used.

In summary, relatively few studies employ forest planning models that first identify vulnerable forest stands and subsequently adapt management practices to reduce the vulnerability to wind damage. Among these studies, the planning horizons are often short, and heuristic techniques are frequently used to solve the resulting optimization problems. However, optimization models reliant on heuristic methods have a significant limitation: they cannot guarantee that the optimal solution to the stated problem is achieved. Moreover, determining and applying appropriate parameters to guide the heuristic process can be challenging and is not always straightforward. Another limitation is that there are few decision support systems available for practical use by forest decision makers that include the possibility of using heuristic methods to address forest planning problems

The objective of this study is to present and assess a long-term forest planning model designed to identify the optimal forest management accounting for the vulnerability of forests to wind damage. Contrary to heuristic approaches, the optimization model is specifically structured to be solved with exact solution techniques. The main decision in the model relates to how each individual stand should be managed throughout the planning horizon to meet traditional long-term forest management objectives and to account for the vulnerability to wind damage. In our study, consideration of wind damage is included by banning final fellings in stands adjacent to stands with high vulnerability to wind damage and the vulnerability is estimated with a sensitivity index based on approximation from Lagergren et al. (2012). The model for harvest scheduling is evaluated using a case study area spanning 2450 hectares in southern Sweden, considering a planning horizon of 70 years.

Material and methods

Description of the planning problem

We include consideration of the forest vulnerability to wind damage in a typical and traditional forest planning problem; see Table 1 for a mathematical description of the planning problem. The planning problem consists of selecting one treatment program for each stand within the forest holding so that the net present value (NPV) is maximized (Eq. 1, 5 and 6). Each treatment program consists of a series of management activities (e.g., thinning, final felling followed by regeneration, or no management at all) from period 1 to the end of the planning horizon. The objective is subject to an even flow of timber harvest through time; in other words, the harvest level in one period should not differ by more than a certain percentage from the average harvest level over all planning periods (Eq. 2 and Eq. 3). Consequently, this part of the model is an example of a standard Model I formulation (Johnson and Scheurman, 1977).

To decrease the vulnerability to wind damage, the traditional planning model is extended with a new restriction that prohibits final felling in stands adjacent to stands with high vulnerability to wind damage, i.e. stands that share a common border (Eq. 4). For each stand and each period, a total sensitivity index (TSI)[0,1] is calculated based on the stand characteristics and the management performed in the stand (for a detailed description of the sensitivity index see next section). If the TSI for the stand, treatment program, and period is equal to or higher than a predefined threshold value, then felling in any of the adjacent stands (i.e., stands that share a common border) is banned. This user-defined threshold value is hereafter called Threshold-TSI and should not be mixed up with the TSI value that is calculated to describe how vulnerable a stand is to wind damage based on stand characteristics. If the user sets the Threshold-TSI value to a value close to 1, the planning model would tend to allow final felling in almost all stands. On the other hand, if the Threshold-TSI value is set close to 0, felling in many stands will not be allowed since almost all stands will have a higher TSI than 0.

Calculation of vulnerability for wind damage

The TSI for wind damage is calculated at the stand level for each planning period after any potential management activity takes place in the stand. Thus, it is calculated for each stand, treatment program, and period. It relies upon a set of indices that describe the relative basal area, allometric index, and height of a specific tree in relation to total stand basal area as well as the stability of the stand after a thinning (root stability index). The range of possible TSI values spans from zero to one. The higher the value, the more vulnerable the stand is to being damaged by wind. The calculation of the TSI in this study is an approximation from Lagergren et al. (2012). The model developed by Lagergren et al. (2012) might be considered an empirical model that includes additional relationships and parameters often found in mechanistic models. The use of this specific model in our study is based on its ability to be integrated into Heureka (the forest management decision support system used in this study).

Table 2
The definitions for the different management strategies.

Management strategy	Definitions
Business as usual (BAU)	This strategy includes one to three thinnings up to a tree height of 25 m and final felling up to 30 years after the lowest accepted final felling age according to the forestry act has been reached. At the time of final felling it is assumed that 5 % of the stand area is left for nature conservation.
Adaptation forestry (ADA)	This strategy is similar to the BAU strategy but limits the number of thinnings to a maximum of one at a maximum tree height of 20 m
Broadleaf adaptation forestry (BADA)	This strategy is like the ADA strategy, but more broadleaves are left in the forest at precommercial thinning and thinning

Table 3
The settings for the different cases A-D concerning potential treatment programs and accepted treatments in stands adjacent to vulnerable stands (stands with high TSI values).

Cases	Potential treatment program from strategies[1]	Treatments in stands adjacent to vulnerable stands	
		Thinning	Final felling
A	BAU, ADA, BADA	Accepted	Banned
B	BAU, ADA, BADA	Banned	Banned
C	BAU	Accepted	Banned
D	BAU	Banned	Banned

[1] A potential treatment program without any management activities is included in all cases.

The stand level TSI is calculated as follows:

$$TSI = RSI * \frac{\sum_{n=1}^{N} BA_n * AI_n * HI_n}{\sum_{n=1}^{N} BA_n}$$

Where BA_n is the basal area (cm^2) of tree n and N is the total number of trees in the stand, AI_n and HI_n are respectively the allometric index and the height index of tree n. RSI is the root stability index of the stand. AI_n, BA_n and HI_n are first calculated at the tree level and, thereafter, included in the calculation of stand level TSI.

The tree Height Index (HI_n) informs of how much a given tree (n) stands out above other trees in the same stand. It is calculated based on the effective tree height (h_{E_n}, m) and the average stand height (g, m). The g provides an estimation of the shelter a tree gets from other trees within the same stand, as well as how much shelter the stand gives to surrounding stands. The h_{E_n} equals the height of the tree for conifer species and only half of the height for broadleaf species (Lagergren et al., 2012).

$$HI_n = \frac{h_{E_n} - g}{30} + 1$$

where

$$g = \frac{\sum_{n=1}^{N} h_n * BA_n}{\sum_{n=1}^{N_i} BA_n} \text{ and } h_{E_n} = h_n \times \begin{cases} 1 \textit{ for conifer sp.} \\ 0.5 \textit{ for broadleaf sp.} \end{cases}$$

Where h_n is the height (m) of tree n. The HI_n will have little significance in stands managed under even-aged management, because this silviculture strategy will very likely produce trees with a similar height and therefore the index in this case will be close to 1. For uneven-aged management or unmanaged stands, this index will inform how

Table 4
Solution times and percentage reduction in NPV between the cases with a Threshold-TSI of 1.0 compared to the other cases and the percentage reduction of the shape index (SI) between the cases with a Threshold-TSI of 1.0 and a Threshold-TSI of 0.1 or 0.2.

	All strategies - thinnings accepted					All strategies - thinnings banned				
Threshold - TSI	Case	Reduction of NPV	Reduction of SI – Ver 1	Reduction of SI – Ver 2	Solution time (s)	Case	Reduction of NPV	Reduction of SI – Ver 1	Reduction of SI – Ver 2	Solution time (s)
	A 0.0	94,7 %			0,5	B 0.0	94,7 %			0,7
0,1	A 0.1	54,8 %	45,5 %	52,6 %	85,202,1	B 0.1	59,8 %	46,8 %	53,2 %	1660,6
0,2	A 0.2	10,7 %	25,0 %	32,8 %	312,8	B 0.2	20,9 %	26,8 %	41,3 %	2728,0
0,3	A 0.3	1,7 %			447,1	B 0.3	2,5 %			529,0
0,4	A 0.4	0,7 %			24,8	B 0.4	1,3 %			114,4
0,5	A 0.5	0,2 %			23,3	B 0.5	0,6 %			15,0
0,6	A 0.6	0,1 %			17,2	B 0.6	0,3 %			18,8
0,7	A 0.7	0,0 %			19,2	B 0.7	0,1 %			17,0
0,8	A 0.8	0,0 %			19,7	B 0.8	0,0 %			12,3
0,9	A 0.9	0,0 %			20,25	B 0.9	0,0 %			16,0
1	A 1.0	0,0 %	0,0 %	0,0 %	13	B 1.0	0,0 %	0,0 %	0,0 %	22,3

	Only BAU and Unmanaged - thinnings accepted					Only BAU and Unmanaged - thinnings banned				
Threshold - TSI	Case	Reduction of NPV	Reduction of SI – Ver 1	Reduction of SI – Ver 2	Solution time (s)	Case	Reduction of NPV	Reduction of SI – Ver 1	Reduction of SI – Ver 2	Solution time (s)
0	C 0.0	99,4 %			0,7	D 0.0	99,4 %			0,3
0,1	C 0.1	63,8 %	48,6 %	37,1 %	1804,3	D 0.1	88,1 %	54,5 %	50,0 %	27,7
0,2	C 0.2	20,5 %	28,5 %	13,7 %	18,714,5	D 0.2	55,9 %	33,1 %	27,4 %	1963,4
0,3	C 0.3	3,6 %			91,65	D 0.3	21,0 %			1455,8
0,4	C 0.4	1,2 %			6,82	D 0.4	7,7 %			271,1
0,5	C 0.5	0,3 %			2,7	D 0.5	2,8 %			35,0
0,6	C 0.6	0,1 %			1,7	D 0.6	0,9 %			2,2
0,7	C 0.7	0,0 %			2,6	D 0.7	0,1 %			1,5
0,8	C 0.8	0,0 %			1,5	D 0.8	0,0 %			1,2
0,9	C 0.9	0,0 %			1,7	D 0.9	0,0 %			2,7
1	C 1.0	0,0 %	0,0 %	0,0 %	2,4	D 1.0	0,0 %	0,0 %	0,0 %	1,0

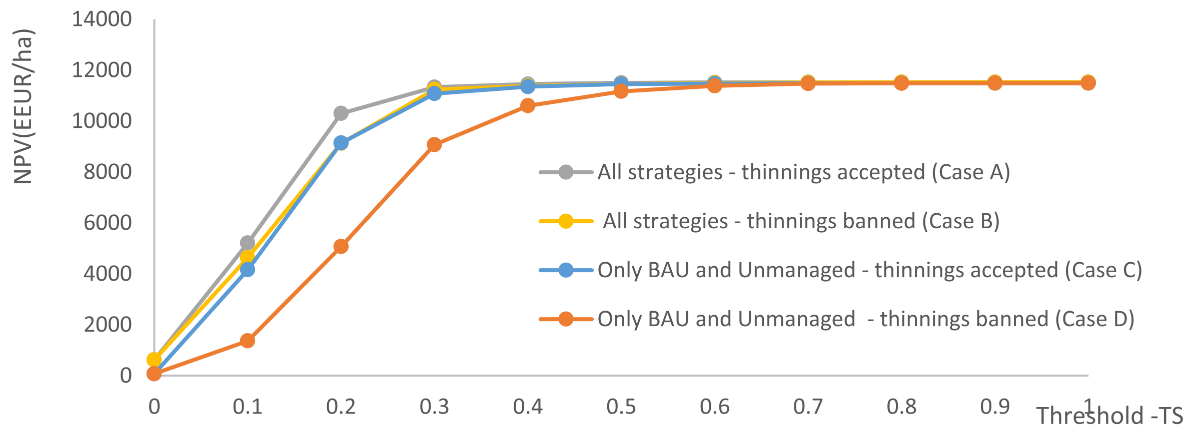

Fig. 1. Trade-off curves between NPV and the value on the Threshold-TSI, i.e., the user defined value on what constitutes high vulnerability for wind damage. Thinning's accepted means that thinning's in stands adjacent to vulnerable are still accepted and thinning's banned means that thinning's in stands adjacent to vulnerable stands are banned.

vulnerable the tree is to wind damage.

The Allometric-relationship Index (AI_n) of tree n is calculated based on the tree height and diameter and adjusted by a constant associated to the specific species group to which the tree belongs (k_{sp}). The AI informs how susceptible a tree is to being damaged by a windthrow without taking into account other trees in the stand or other stands in the landscape. The relationship between the height and the diameter of a tree has been identified by several studies as strongly connected to wind damage (Peltola et al. 1999a; Gardiner et al. 2000).

$$AI_n = \frac{h_n - k_h}{d_n + k_d} k_{sp}$$

Where d_n(cm) is the diameter of tree n. k_h is the minimum height (m) that a tree would need to be to be damaged by wind and k_d reduces the dependency of stem diameter. The values of k_h and k_d are the constant minimum height for occurrence of wind damage and a constant that reduce the dependency of the diameter, respectively set to 5 m and 12 cm (Lagergren et al. 2012). k_{sp} is a tree species-specific value and can be found in Table 2, Table 3, Table 4, Table 5 in Appendix A. For trees smaller than 5 m the value of AI_n is set to zero.

The Root Stability Index (*RSI*) helps assess the decrease in stability that a stand endures after a thinning has been performed in the stand. As mentioned before, the forest sensitivity to storm damage is affected by how and when thinning or any other activity that implies the removal of timber is performed. This loss in stability could be due to the fracture of the web of living roots that secure the trees into the ground or because the trees have grown in a dense stand favoring height growth versus diameter growth. After thinning is carried out, the trees need a time span to regrow to a steadier shape. The RSI is calculated for each period and at the stand level as described below

$$RSI = a + b * \exp(c * t)$$

Where a, b, and c are parameters that depend upon the intensity of the thinning performed and t is the time since last thinning or other intermediate management treatment that includes timber removal. The parameter values are found in Table 6 in Appendix A. If no intermediate treatment has been performed in a specific stand in a specific period, the *RSI* is set to 0.1.

Case study

Forest data

The planning model described above was evaluated for a forest property located in southern Sweden (56°37′ N, 15°30′ E). This area was selected because it is, in many respects, typical for managed forests in this part of Sweden, and it represents a size relevant to the management of large forest holdings. The total area is 2450 hectares of which 2445 hectares is productive forestland (forest with a mean annual increment greater than 1 $m^3 ha^{-1} year^{-1}$) divided into 751 stands. The forest data for the area was collected in 2019. The forest is dominated by Norway spruce (*Picea abies* L.) (78 % of the standing volume) followed by Scots pine (*Pinus sylvestris* L.) (18 %) and birch (*Betula* spp.) (4 %), and the mean standing volume is 200 m^3 ha^{-1}. The mean age is 46 years, and 25 % of the area is older than the lowest accepted final felling age according to the Swedish forest legislation, see also Fig. 1 in Appendix B.

The Heureka system

The Heureka system, version 2.19, (Lämås et al., 2023) was utilized to simulate stand treatment programs over a 70-year planning horizon, divided into 14 five-year periods. The simulations included the computation of harvest volumes, TSI (Treatment Sensitivity Index) for each stand treatment program and period, and net present value (NPV) calculations for each program. The Heureka system was also used to formulate the optimization problem.

Heureka is an advanced forest decision support system developed for Sweden, used both in research and practical forestry. In Heureka, data on current forest conditions, potential management actions, and models for different ecosystem processes form the basis to simulate forest dynamics and management through time. The Heureka application PlanWise, which was used in this study, applies a two-step approach building on simulations of forest growth and yield in combination with optimization. The first step is to simulate several different potential treatment programs for each stand and management strategy. A management strategy sets the frame for different management activities to be simulated over time. Management strategies can differ in forest management regime (e.g. no management, even-aged management, or uneven-aged management) or types of management activities within a management regime (e.g. type of regeneration, number of thinnings). Connected to each treatment program is the calculation of the NPV of future forest activities together with periodic output information for different indicators connected to economic, ecological and social values. These outputs are calculated based on models projecting forest dynamics, such as empirical growth models (Fahlvik et al., 2014), mortality models (Fridman and Ståhl, 2001) and models for in-growth (Wikberg, 2004) on an individual tree basis. The second step when using Heureka PlanWise is to identify the combination of treatment programs for all stands that optimizes user-defined objectives and fulfils stated constraints by applying linear programming (LP) or mixed integer programming (MIP).

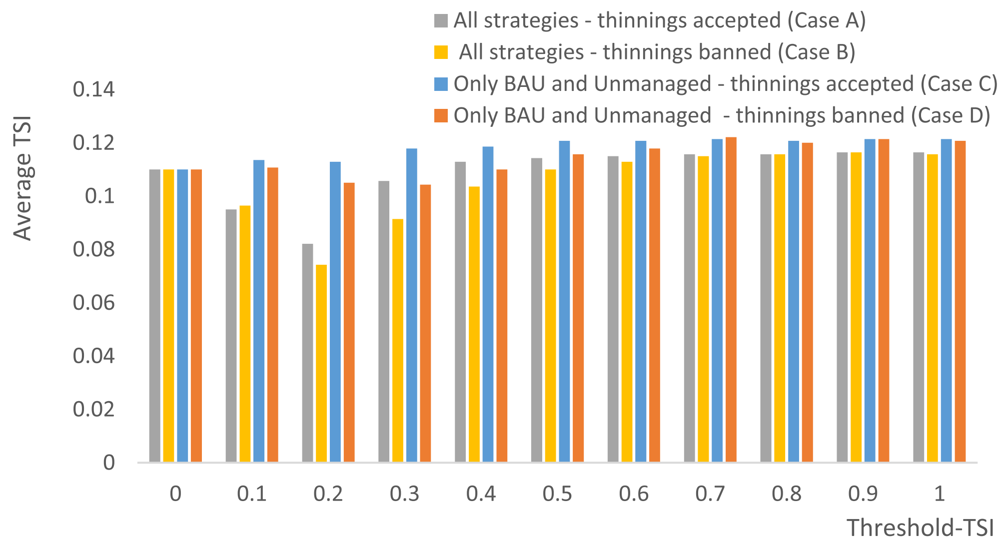

Fig. 2. The average Total Sensitivity Index (TSI) over all periods for all cases for different Threshold-TSI. Thinning's accepted means that thinning's in stands adjacent to vulnerable are still accepted and thinning's banned means that thinning's in stands adjacent to vulnerable stands are banned.

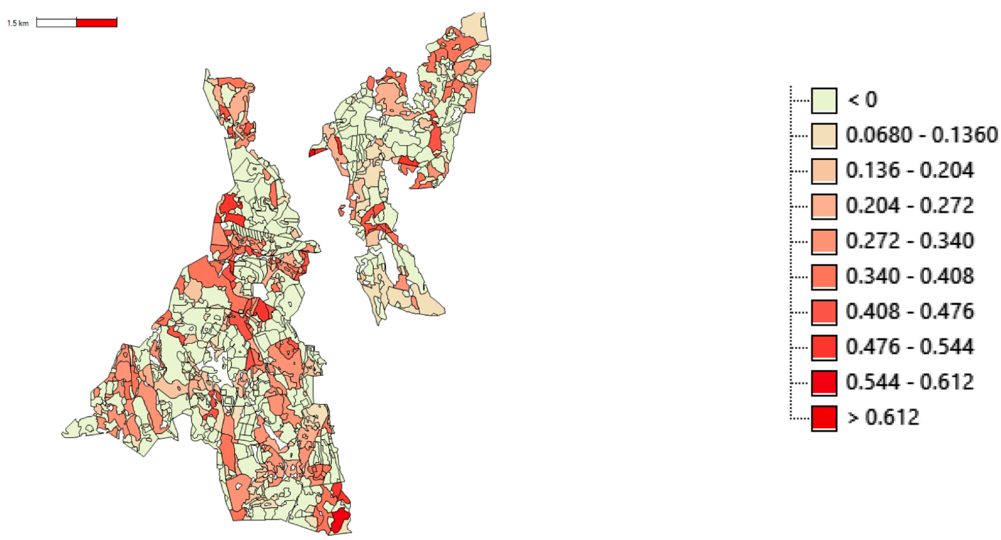

Fig. 3. TSI values in each stand in the beginning of the planning horizon.

Generation and selection of treatment programs

For every stand within the property, up to 20 potential treatment programs were generated for each of three different management strategies, see Table 2. The first strategy, named business as usual (BAU) represents ordinary wood-production oriented forest management, the second strategy, named adaptation forestry (ADA), is similar to the BAU strategy but limits the number of thinnings and the third strategy, named broadleaf adaptation forestry, BADA, is like the ADA strategy, but more broadleaves are left in the forest at precommercial thinning and thinning. In addition to the programs connected to the management strategies described in Table 2, one treatment program without any management activities during the planning horizon was also generated in all the strategies. This resulted in an average of 25 treatment programs being generated for every stand within the case study area. Management costs and timber prices used for calculating the NPV for each schedule were based on a timber price list retrieved from the forest owner's organization in southern Sweden, considered to be representative of the region. The real interest rate used to calculate the NPV was set to 2.5 %. Importantly, the treatment programs only include average mortality by various causes and not any specific storm damage.

To better understand the implications of different Threshold-TSI definitions, the optimization model was first solved 11 times with different settings on the Threshold-TSI (0.0, 0.1, 0.2, …, 1.0), (cases A0.0 - A1.0 in Table 4). In all these cases, treatment programs from all three strategies (BAU, ADA, and BADA) were allowed. Moreover, the total volume harvested in each period was not allowed to increase or decrease by >10 % from the average harvest level over all periods, i.e. γ and μ were set to 0.1. To investigate the consequences of also banning thinnings in stands adjacent to vulnerable stands (high TSI values), the model was solved once more for each of the values on the Threshold-TSI (cases B0.0 - B1.0 in Table 4), i.e. in these cases the definition of m_{kjp} is changed to that it is 1 if treatment program j for stand k includes a final harvest or thinning in period p. Finally, to investigate the effect of adapting the forest management at the stand level to create less vulnerable forests, the model was also solved without the possibilities to select schedules representing adaptation management, i.e., by excluding the possibilities to select treatment programs from the set of management strategies called ADA and BADA. This was done both with thinning allowed as well as not allowed (cases C0.0 - C1.0 and cases D0.0 - D1.0,

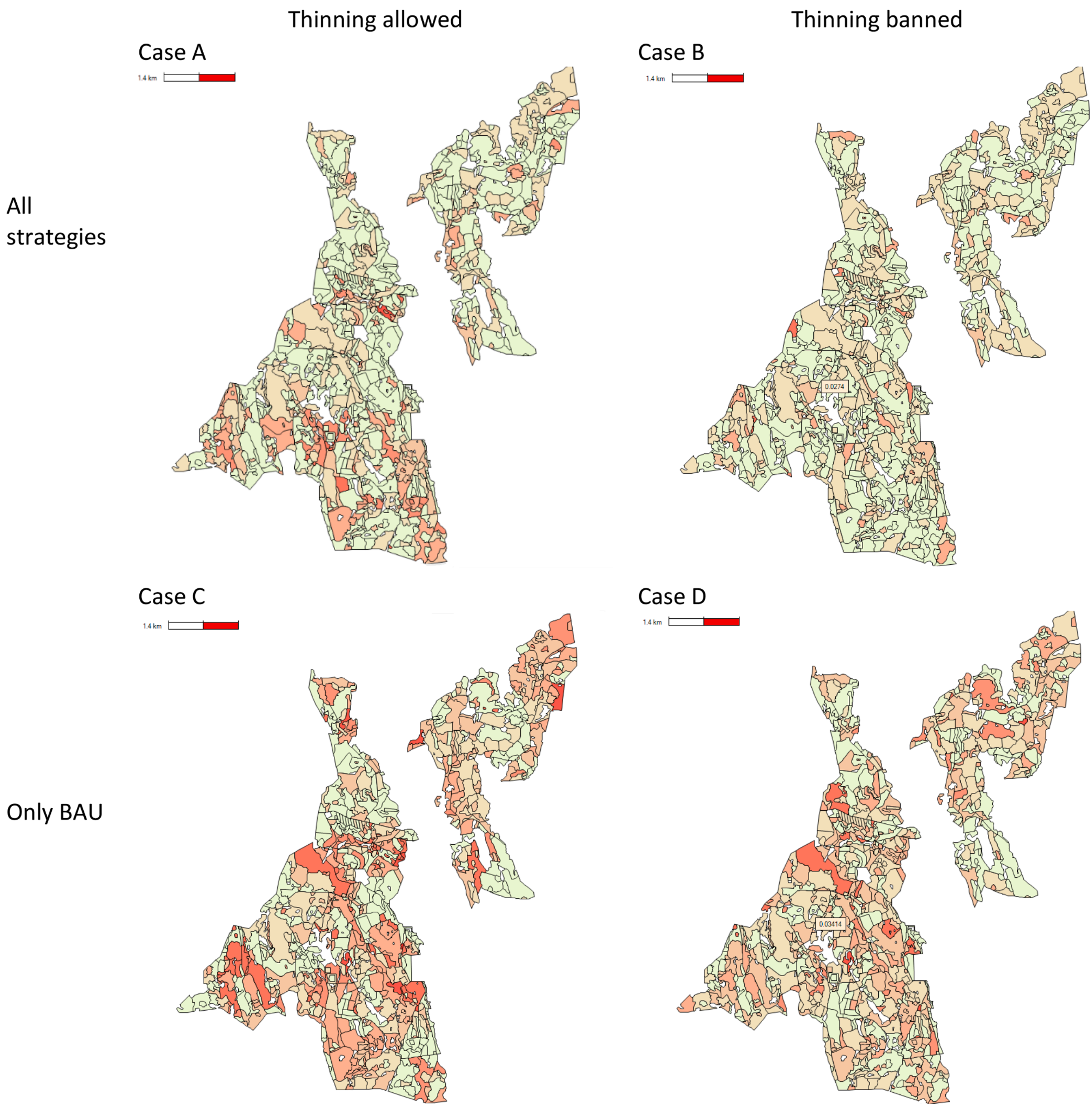

Fig. 4. TSI values in each stand at the end of the planning horizon for Threshold-TSI value 0.2 for the cases A0.2 (upper left), B0.2 (upper right), C0.2 (lower left) and D0.2 (lower right). For legend see Fig. 5. Thinning's accepted means that thinning's in stands adjacent to vulnerable are still accepted and thinning's banned means that thinning's in stands adjacent to vulnerable stands are banned.

respectively, in Table 4). For a summary of cases, see Table 3.

The optimization problem was formulated using the optimization module within Heureka built on Zimpl (Koch, 2005) for forming the MIP matrix and solved using Gurobi 9.1 with a branch and bound algorithm. The GAP tolerance was set to 0.01 %, meaning that once the solver found an integer solution within 0.01 % of the theoretical optimal, the solution procedure was cancelled, and the solution was declared optimal.

Evaluation of spatial layout

To evaluate the spatial layout of thinning and final felling areas for different values of the Threshold-TSI, a shape index (SI) was calculated for the final solution for cases with a Threshold-TSI of 0.1, 0.2, and 1.0. The SI is a geometric characteristic of an area that measures how compact the area of interest is. In essence, it represents the deviation of the shape of a patch from a perfect circle. In other words, the SI of a patch with perfect circularity would equal 1 and the SI of other irregular shapes would be greater than 1. This index has been used in several studies to describe the degree of fragmentation of old forests in the landscape (Baskent and Jordan, 1995; Ripple et al. 1991). The SI is calculated as:

$$SI_p = B_p / \left(2\sqrt{A_p * \pi}\right)$$

where SI_p is the SI in period p, A_p is the total area of stands representing the area of interest and B_p is the total perimeter of the same stands. In

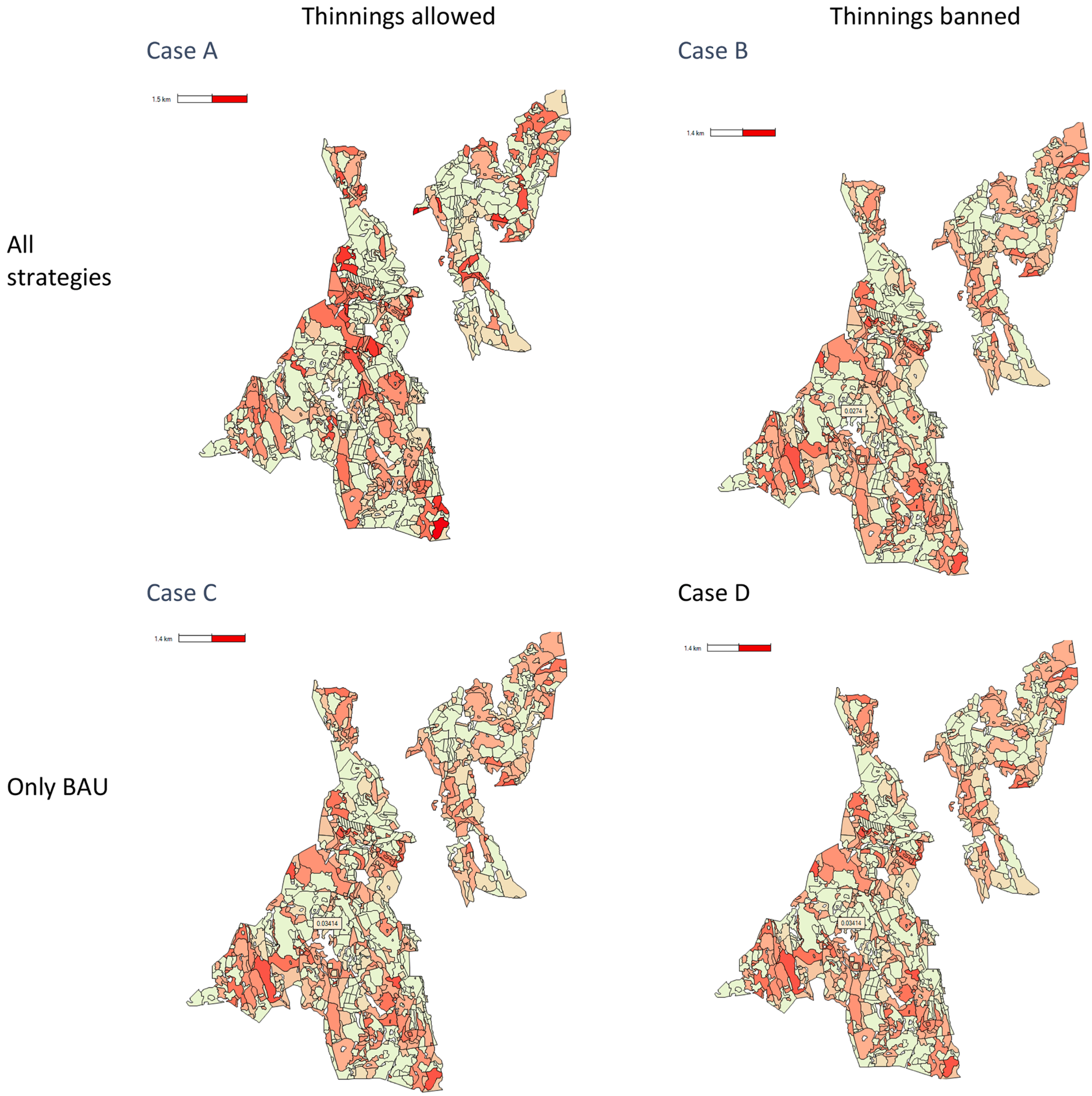

Fig. 5. TSI values in each stand at the end of the planning horizon for Threshold-TSI value of 1.0 for the cases A1.0 (upper left), B1.0 (upper right), C1.0 (lower left) and D1.0 (lower right). For legend see Fig. 5. Thinning's accepted means that thinning's in stands adjacent to vulnerable are still accepted and thinning's banned means that thinning's in stands adjacent to vulnerable stands are banned.

this study, two different versions of the SI were calculated. In version 1, only final felling areas in each period were considered and in version 2, both thinning and final felling areas were considered when calculating the landscape level SI.

Results

The trade-off curve, i.e. the graphical representation of the relationship between NPV and the Threshold-TSI (the user-defined definition of what constitutes a vulnerable forest to wind damage), shows that decreasing the value of the Threshold-TSI causes a reduction in NPV (Fig. 1), i.e., decreasing the vulnerability of the forest to wind damage comes with a loss in potential NPV. The percentage reduction in NPV and SI between the cases with a Threshold-TSI of 1.0 compared to the other cases is shown in Table 4.

Averaged over all periods, the TSI value decreased for all cases with a decrease in Threshold-TSI value until the Threshold-TSI value decreased to 0.2 (Fig. 2). In addition, giving the model the possibility to select programs from all strategies reduced the average TSI in the property for almost all Threshold-TSI. The TSI values over time for a Threshold-TSI of 0.2 and 1.0 are shown in Fig. 3 in the appendix B. These cases were selected to exemplify the effect on vulnerability to wind damage over time when the Threshold TSI is set to a high versus a low value. The TSI in each period decreased until period 6, 7, or 8 followed by an increase in the later part of the planning horizon.

TSI values on a stand level in the beginning and at the end of the

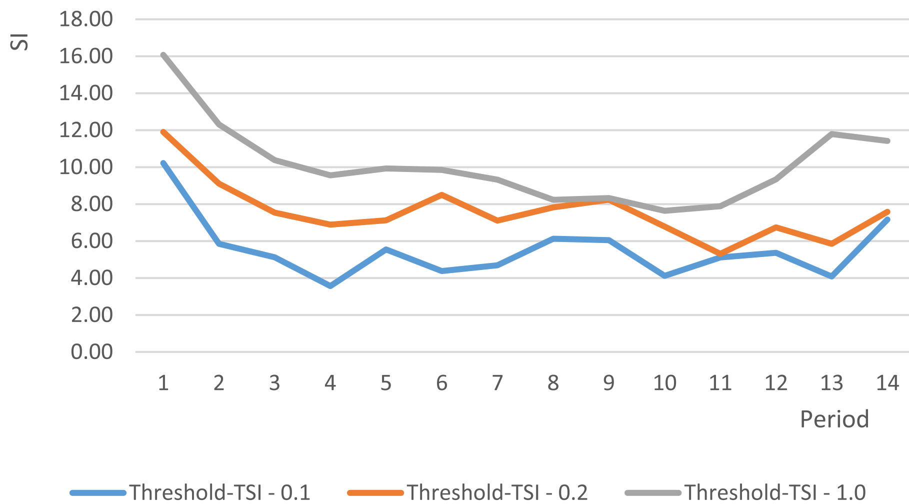

Fig. 6. The trends in shape index (SI) over time for version 1 (i.e. only final felling areas in each period were considered when calculating the landscape level SI) for the cases with all strategies and where thinnings are accepted adjacent to vulnerable stands (case A 0.1, A 0.2 and A 1.0.

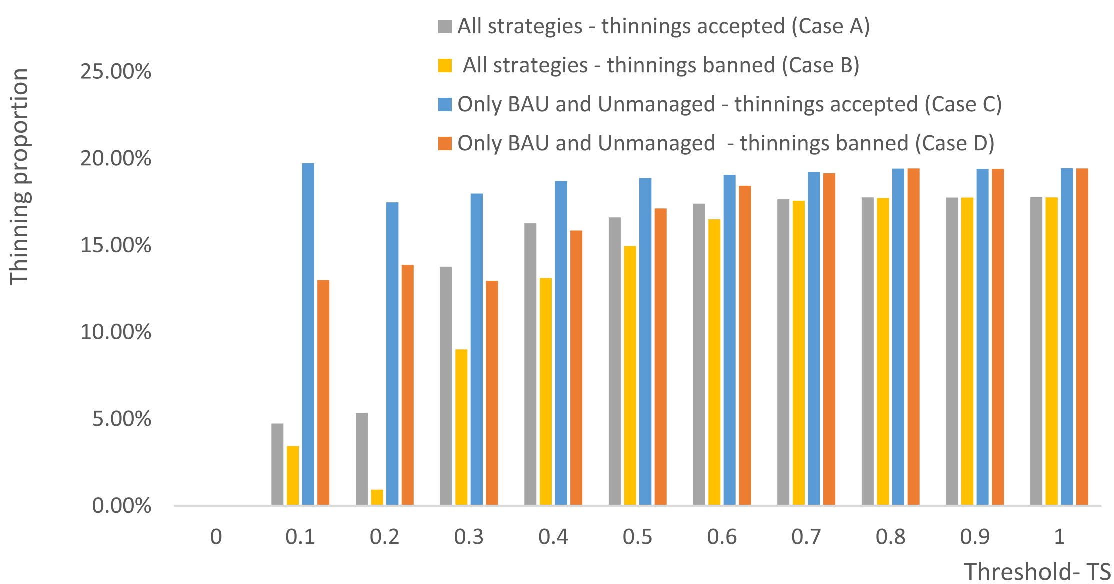

Fig. 7. The average thinning volume proportion of total harvest volume over all periods for all cases. Thinning's accepted means that thinning's in stands adjacent to vulnerable are still accepted and thinning's banned means that thinning's in stands adjacent to vulnerable stands are banned.

planning horizon for the cases with a Threshold-TSI of 0.2 and 1.0 are shown in Fig. 3, Fig. 4, and Fig. 5, respectively. These cases were selected to exemplify the effect of vulnerability to wind damage on a stand level when the Threshold-TSI is set to a high versus a low value.

The SI values for the spatial layout of final fellings over time are presented in Fig. 6 for cases A 0.1, A 0.2, A 1.0. A similar figure is available in Fig. 7 in Appendix B for cases B 0.1, B 0.2, and B1.0. The SI value follows a consistent pattern; for each period the higher the value of the Threshold-TSI, the higher the value of SI.

To evaluate whether the proposed model has any effect on the thinning activities, the thinning proportion in each period for each case was recorded (Fig. 8). It seems that with a decreased value on the Threshold-TSI, the thinning proportion decreases in almost all cases except for the cases where only strategies from BAU and unmanaged were available and thinnings were accepted (cases C). In addition, the average final felling age seemed to increase with a low value on the Threshold-TSI (see Fig. 9 in the appendix).

For cases A and B, i.e., the cases where all four management strategies were available, there was a mixture of management strategies, regardless of the value of the Threshold-TSI. However, with a decreasing value on the Threshold-TSI, the proportion of BAU decreased and the proportion of the other strategies increased, both with thinning's allowed (case A, Fig. 8) and not allowed (Case B, see Fig. 10Appendix B).

For all cases, the branch and bound algorithm was able to solve the stated problem within the convergence bound. The solution times were, for most cases, <5 min. However, when the Threshold-TSI was set to 0.1–0.3, the solution time increased substantially (Table 4).

Discussion

Our results suggest that it is possible to use the proposed model to include consideration of wind damage in long-term forest planning. The model includes the ability to prohibit final felling or other management activities, such as thinning, in stands adjacent to those with high vulnerability to wind damage. This is important because avoiding the creation of new forest edges that are close to vulnerable forest stands is likely to decrease the vulnerability to wind damage. In addition, the results show that our model decreases the vulnerability to wind damage

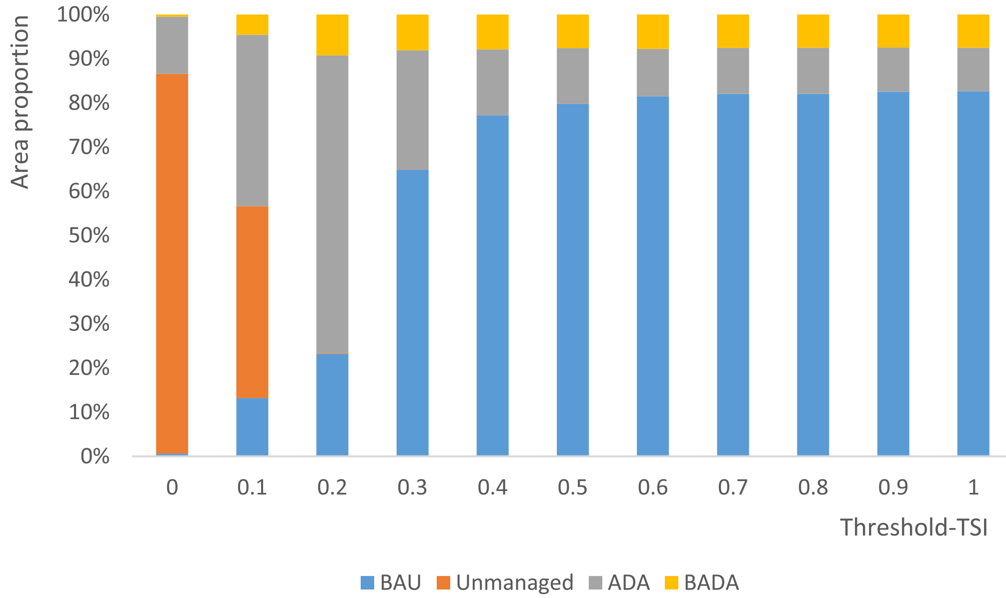

Fig. 8. Proportion of management strategies for different values on the Threshold-TSI for cases A, i.e. the cases where all strategies are available and thinnings are accepted. BAU represents ordinary wood-production oriented forest management. ADA is similar to the BAU strategy but has a limitation on one thinning a maximum at a maximum tree height of 20 m BADA is a similar strategy to ADA but with a higher share of broadleaved species left in the forest after pre-commercial and commercial thinnings. The Unmanaged strategy includes no management at all.

at the stand and property level, especially when the model has the possibility to select treatment programs from all management strategies compared to using only treatment programs available within the BAU strategy. Allowing each stand to choose from all strategies enables tailored management, reducing wind damage vulnerability and facilitating harvest in neighboring stands.

In this study, we use an adapted approximation of the storm susceptibility model developed by Lagergren et al. (2012). Lagergren's model is primarily empirical but incorporates mechanistic features, making it highly compatible with a forest decision support system and dynamic vegetation models for assessing wind damage vulnerability at the stand level. However, our implementation is not intended as a predictive tool for estimating the probability of damage in specific regions or under particular conditions. Instead, it is designed to assist decision-makers in relative comparisons of different management alternatives and can be used for identifying the optimal timing and locations of management activities e.g., final fellings. It is also important to note that our implementation does not account for landscape characteristics such as topography or exposure, in the TSI calculation. Instead, it relies primarily on indices that describe stand characteristics to estimate potential wind damage vulnerability. We understand the limitations this could provide to this study. Future development of the model could incorporate spatial characteristics, which would likely enhance simulations of how management activities impact surrounding stands. Currently, tree height and root stability are the critical variables in our model. As such, the model is particularly sensitive to intermediate management treatments, such as thinning.

When applying the optimization model, the user-predetermined definition of vulnerability- i.e., the Threshold-TSI - is key to understanding the results. Decreasing the value of the Threshold-TSI had a large impact on the NPV across all the cases (Fig. 11). Using a low value for the Threshold-TSI leads to a decrease in the NPV, particularly in scenarios where only management strategies representing BAU forestry were available and both final felling and thinning are banned in stands adjacent to the stand with high vulnerability (case D). This is because the lower the TSI threshold, the higher the number of stands that qualify as "highly vulnerable". Consequently, a larger share of the landscape is subject to final felling or thinning restrictions, reducing the economic return from the management activities. When the Threshold-TSI is set to zero, all the stands are considered susceptible to wind damage and no active management activity are allowed to happen.

Following the same logic, cases where thinning was also banned in adjacent stands produced a lower NPV compared to cases where only final felling was not allowed.

Regarding the economics analysis, it should be noted that the NPV calculation in this study does not include the financial savings from decreasing the vulnerability to wind damage or the potential economic losses in the event of a storm. Additionally, this study does not account for the potential harvest costs savings from aggregating the harvest areas on the same period. This aspect could be addressed in a future studies by favoring stand aggregation into the optimization model. In addition, an advantage of the model is that it gives the user the possibility to generate a range of plans using different values on the Threshold-TSI and then select the plan with an acceptable decrease in NPV.

A similar pattern is found when addressing the spatial layout of the management activities. Using a low value on the Threshold-TSI will result in large aggregates of harvesting areas which can be seen in the resulting SI of the harvest areas (Fig. 6). A lower Threshold-TSI produces smaller SI values in each period compared to a higher Threshold-TSI. This is because a low predefined TSI forbids some or all the management activities in more areas of the forests, allowing the management operations to happen in the surroundings of a reduced number of stands, instead of being spread throughout the landscape. This could be positive or negative depending on what values are considered. It is positive if the interest is in reducing the vulnerability to wind damage and it is economically profitable since the cost of harvesting would decrease. However, larger final felling areas may be negative from an ecological and social point of view (Pawson et al. 2006).

Applying the model affects the thinning proportion; a low Threshold-TSI decreases the thinning proportion compared to a high Threshold-TSI value when treatment programs from all management strategies are accepted (Fig. 7). This could be prohibited by including new restrictions in the planning model demanding a certain thinning proportion. However, this would probably increase the solution time considerably. Our model also has an impact on the proportion of different management strategies. It seems to be more beneficial to use a variation of management strategies when including consideration to wind damage in forest planning. This result is in line with many other studies showing that forestry that aims at balancing different values requires a variation in management practices (Díaz-Yáñez et al. 2020; Eyvindson et al. 2018; Eggers et al. 2022). Threshold-TSI values in the range 0.3 - 1.0 have no or negligible effects on average final felling age over all periods (Fig. 12). When lowering the Threshold-TSI from 0.3 to 0.2, average final felling ages increased notably, and this coincides with the drop in NPV (see Fig. 13). Moreover, higher Threshold -TSI values (0.3 - 1.0) cases with all management strategies had lower final felling ages compared to cases with only the BAU strategy. This is, however, contrary to the outcome for Threshold-TSI values 0.1 and 0.2. This switch is most likely caused by a notable drop in the use of the BAU regime when turning from Threshold-TSI values 0.3 to 0.2 when all management strategies are included.

Conclusion

One of the biggest challenges of strategic forest planning nowadays is to develop new forest management planning models that can account for increased damage vulnerability due to a changing climate, i.e., damages that causes considerable important economic, ecological, and social impacts in forestry. One of the unique aspects of our long term planning model is that the user decides the Threshold-TSI, i.e., the user-defined definition of what constitutes a forest vulnerable to wind damage. This feature provides flexibility and gives the user the freedom to choose their own definition of what constitutes a forest vulnerable to wind damage. Another unique aspect is that the model is spatially explicit, i.e. the model includes the geographical position of harvests and the effect of neighbouring stands. In addition, the model can be included in traditional forest decision support system building on exact solution techniques, which is an advantage since many systems used for forest planning in practical forestry rely on exact optimization methods such as LP or MIP. The model presented in this study can be used for identifying optimal forest management that aims at both fulfilling traditional long-term management goals and avoiding wind damage. Thereby our model will contribute to long-term forest planning aiming at adapting forestry to climate change.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly in order to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Karin Öhman: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **IreneDe Pellegrin Llorente:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Teresa Fustel:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Inka Bohlin:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Tomas Lämås:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Jeannette Eggers:** Writing – review & editing, Writing – original draft, 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.

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Appendix A

The values presented in the following two tables are approximations from the model of Lagergren et al. (2012)

Table 5
Species-specific values of k_{sp} used to calculate the allometric relationship coefficient.

	Pine/Larch	Spruce/fir/other conifers	Broadleaf species
Ksp	0.85	1.70	0.17

Table 6
Coefficients used to calculate the Root Stability Index depending on the percentage of timber volume removed during the thinning operation.

Thinning intensity	a	b	c
$<$ 25 %	0.2978	0.4573	−0.2465
[25 % - 35 %)	0.2001	0.7559	−0.1242
$\geq$ 35 %	0.1538	0.9959	−0.0932

Appendix B

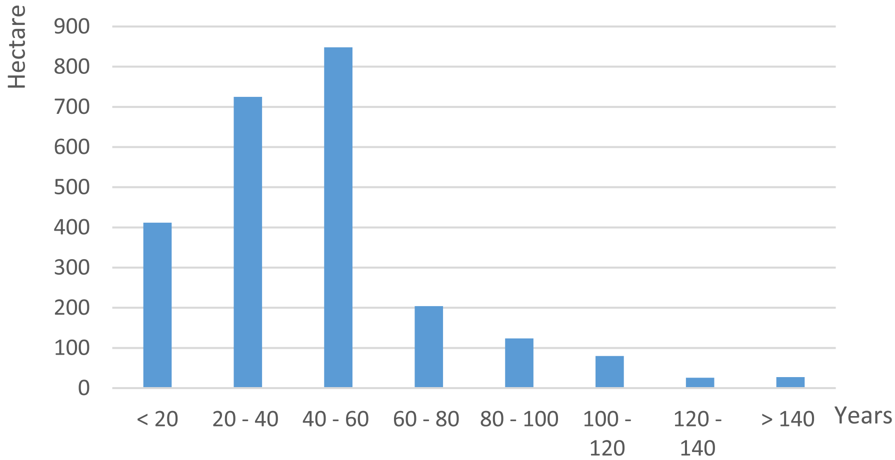

Fig. 9. The initial age-class distribution in the landscape.

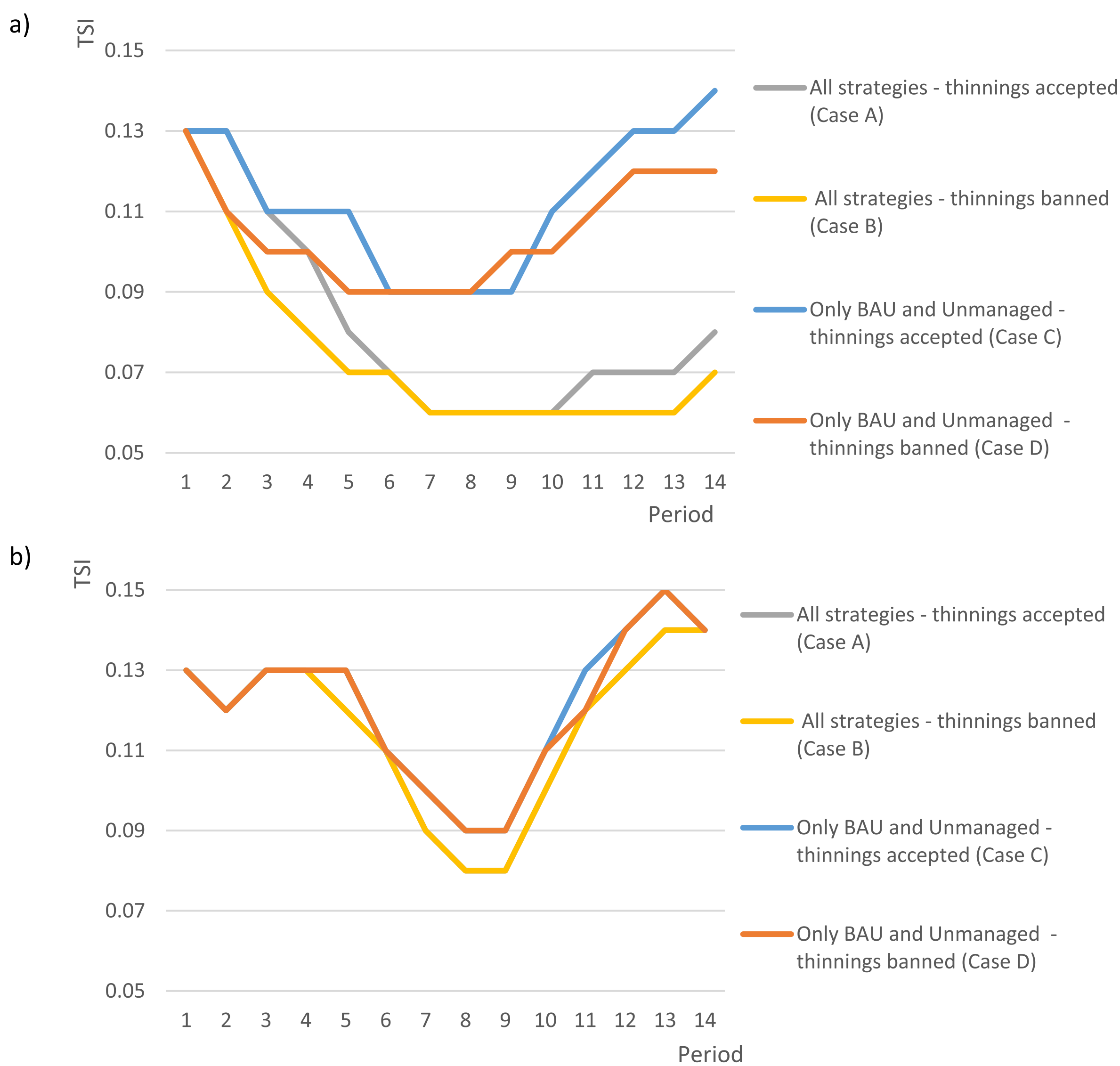

Fig. 10. The average Total Sensitivity Index (TSI) at the property for all cases for a) a Threshold-TSI value of 0.2 and b) a Threshold-TSI value of 1.0. Thinning's accepted means that thinning's in stands adjacent to vulnerable are still accepted and thinning's banned means that thinning's in stands adjacent to vulnerable stands are banned.

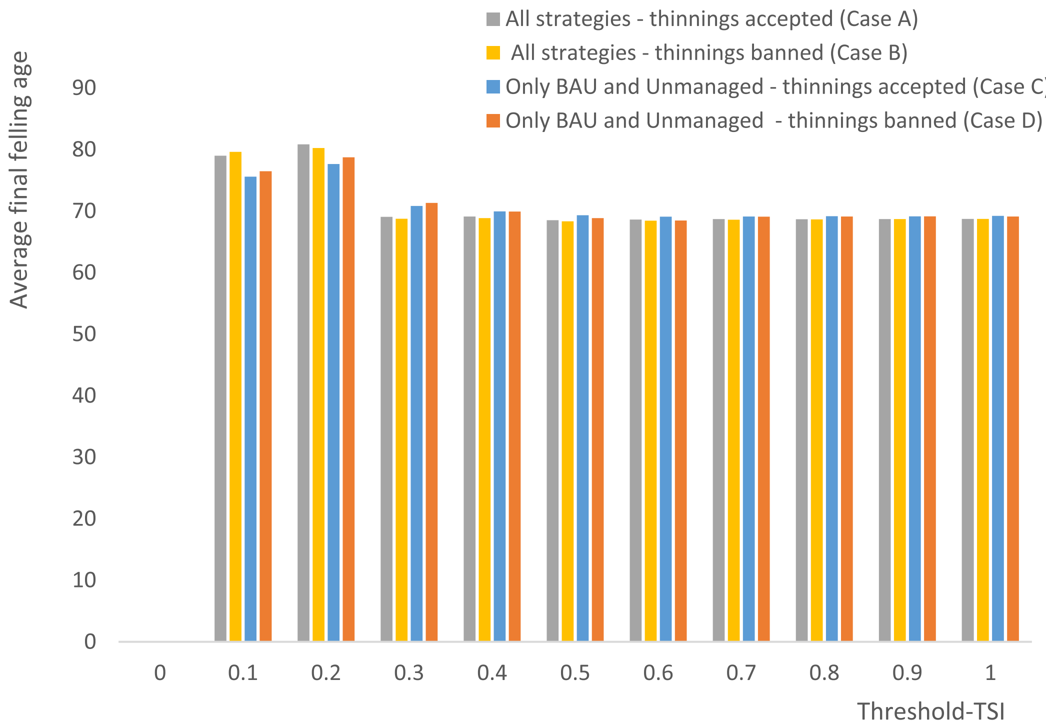

Fig. 11. The average final felling age over all periods for all cases. Thinning's accepted means that thinning's in stands adjacent to vulnerable are still accepted and thinning's banned means that thinning's in stands adjacent to vulnerable stands are banned.

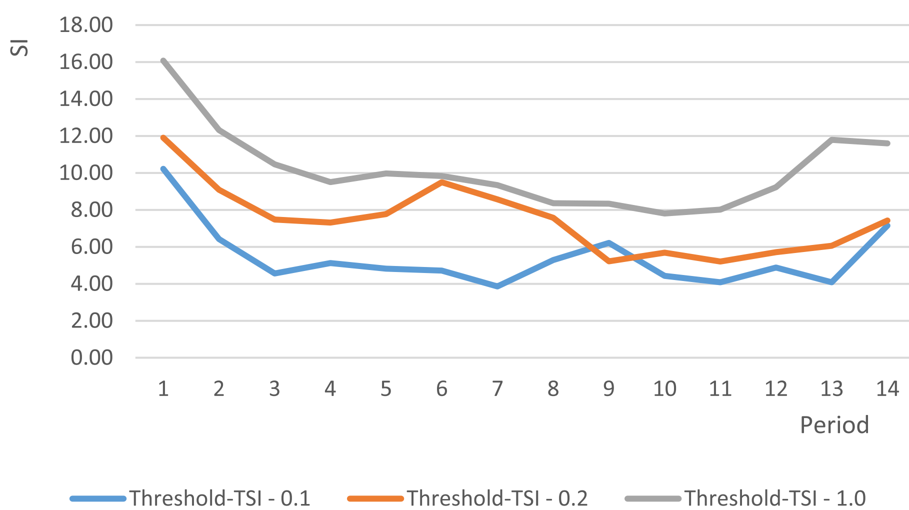

Fig. 12. The trends in shape index over time for final fellings (i.e. version 1.for the cases with all strategies and where both thinning's and final fellings are banned adjacent to vulnerable stands (case B 0.1, B 0.2and B 1.0).

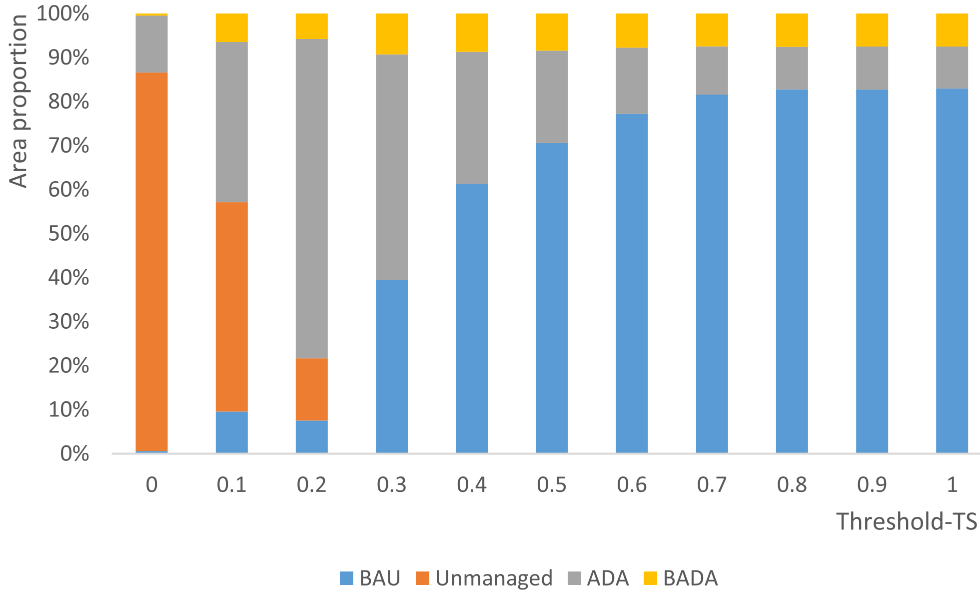

Fig. 13. Proportion of management strategies for different values on the Threshold-TSI for cases B, i.e. the cases where all strategies are available and both final fellings and thinnings are banned. BAU represents ordinary wood-production oriented forest management. ADA is similar to the BAU strategy but has a limitation on one thinning a maximum at a maximum tree height of 20 m BADA is a similar strategy as ADA but with a higher share of broadleaved species left in the forest after pre-commercial and commercial thinnings. The Unmanaged strategy includes no management at all.

Data availability

Data will be made available on request.

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