Trees, Forests and People 11 (2023) 100364

Contents lists available at ScienceDirect

Trees, Forests and People

journal homepage: www.sciencedirect.com/journal/trees-forests-and-people

Development and implementation of a spruce bark beetle susceptibility index: A framework to compare bark beetle susceptibility on stand level

Michelle Nordkvist [a,*], Jeannette Eggers [b], Teresa López-Andújar Fustel [b], Maartje J. Klapwijk [a]

[a] Department of Ecology, Swedish University of Agricultural Sciences (SLU), Box 7044, SE-75007 Uppsala, Sweden
[b] Department of Forest Resource Management, Swedish University of Agricultural Sciences (SLU), SE-90183 Umeå, Sweden

ABSTRACT

The spruce bark beetle (spruce bark beetle) (*Ips typographus*) is one of the major disturbance agents in European forests. Damage by spruce bark beetle is expected to increase in the future, as a result of e.g. increased temperatures. However, not all forest stands are equally vulnerable. Therefore, describing the relative difference in susceptibility of different forest stands to spruce bark beetle infestation and to try to estimate changes in susceptibility under different management or climate scenarios is necessary to support decision making on forest management. We present a spruce bark beetle susceptibility index, which describes the relative susceptibility of forest stands to spruce bark beetle infestation. The index is based on empirical findings and expert opinion, and takes both climatic and stand variables into account. The index can be implemented in forest simulation programs. The susceptibility index was implemented in Heureka, a forest decision support system. To demonstrate the use of the index, simulations were run for three management scenarios: baseline; even-aged management focused on conifers, longer rotation: same as baseline but with longer rotation periods and mixed forest: same as baseline but retaining a higher share of broadleaves. For this purpose, an area of 2451 ha consisting of 751 stands was used. The index value per stand per five-year time period was obtained from the simulations. The index was calculated individually, per management strategy, for all 751 stands and thereafter mean index and harvest volume was obtained for the whole area. Mean susceptibility was higher, and harvest slightly lower, in the longer rotation scenario, compared with the baseline, while there were no differences between baseline and mixed. At individual stand level, the differences are more nuanced and, for example, certain stands have lower susceptibility in the mixed compared with the baseline scenario. The ability to simulate forest development and simultaneously get a measure of spruce bark beetle susceptibility will enable forest owners to identify vulnerable stands and evaluate effects of different management decisions to reduce the risk for future economic losses.

Introduction

The spruce bark beetle (*Ips typographus* L.) is one of the most severe pests in European forest. Unprecedented outbreaks in Central Europe since 2015 and in Sweden since 2018 have changed the forest landscape and potentially the future of spruce (*Picea abies* (L.) Karst.) as a forestry species. The frequency and magnitude of spruce bark beetle outbreaks will most likely increase in the future due to climate warming and high volumes of spruce caused by current forestry practices. During the 20th century the increase in forest disturbance caused by the spruce bark beetle can be attributed to the changes in forest structure with increasing volume of spruce in the landscape (Schelhaas et al. 2003; Seidl et al., 2011). Modelling studies show that climate change will increase the likelihood of spruce bark beetle outbreaks and disturbance (Jönsson et al., 2007; Seidl et al., 2008).

Spruce bark beetle are specialist bark boring insects dependant on mature spruce trees for their development. At endemic population levels, the spruce bark beetle is dependant on either wind-felled or weakened trees for successful colonization. However, when reaching epidemic, outbreak, densities, spruce bark beetles are able to kill standing, healthy spruce trees, causing extensive tree mortality. The onset of spruce bark beetle outbreaks are either big storms or droughts, creating a surplus of breeding material. At epidemic level, the ability of spruce bark beetle to colonize trees also depends on external, i.e. stand, landscape and climatic, factors (Raffa et al. 2008), regardless whether a tree is stressed or healthy.

During the last decades, the focus of forest management has shifted from an exclusive focus on wood production to inclusion of other values, like biological conservation and more recently forest health. Forest health is under threat, and disturbances are expected to increase both in extent, frequency and severity (reviewed by Gauthier et al., 2015). Thus, from the perspective of future forest health, disturbances (both biotic and abiotic) are important to consider in decision making for long-term forest management. However, in decision making risks related to disturbances are often ignored (Knoke et al., 2008, Knoke et al., 2017). Therefore, to guide forest management actions, we developed a spruce bark beetle susceptibility index and implemented it in a forest decision support system (DSS). As the abiotic disturbances underlying spruce

* Corresponding author at: Dr Michelle Nordkvist, Swedish University of Agricultural Sciences, Sweden.
E-mail address: michelle.nordkvist@slu.se (M. Nordkvist).

https://doi.org/10.1016/j.tfp.2022.100364
Received 1 October 2022; Received in revised form 29 November 2022; Accepted 5 December 2022
Available online 9 December 2022
2666-7193/

bark beetle outbreaks, storm and drought, are hard to control for and to predict, one way of preparing for those is to manage the forests in such a way that susceptibility to spruce bark beetle in general is reduced. Therefore, we developed an index on susceptibility to spruce bark beetle rather than risk of damage or outbreak. Susceptibility can be viewed as the extent to which a stand would suffer from bark beetles if/when exposed, disregarding the likelihood of exposure. The purpose is to be able to evaluate the relative extent to which a stand would suffer from spruce bark beetle, compared to other stands or with itself under different types of forest management. By describing which factors contribute to spruce bark beetle stand susceptibility and including that in a forest DSS) decision makers can alter their management actions to reduce the risk of spruce bark beetle disturbance. Including disturbances into DSS, can alter the outcome of the analyses. It has, for example, been shown that including storm disturbance in a DSS shifted which management scenario that resulted in the highest net present value (Hahn et al., 2021). We believe that the susceptibility index we present in this paper, is a tool that will support decision towards prevention of spruce bark beetle damage by assisting forest managers to assess ways to reduce susceptibility.

Aim

The aims of this work is to A) develop, present and describe a spruce bark beetle susceptibility index and B) to demonstrate its use in the forest decision support system Heureka.

Method

Overall description

We developed a susceptibility index that is calculated per forest stand and based on both stand and climate variables (Table 1, Fig. 1). The variables included are hypothesized to contribute to the susceptibility of forest stands to spruce bark beetle infestation. The structure of the index is based on a hazard assessment system called predisposition assessment system (PAS) (Netherer 2003). PAS has previously been used to evaluate the risk of spruce bark beetle at stand level (Nopp et al., 2001; Netherer 2003; Netherer and Nopp-Mayr 2005), and was developed with the motivation that foresters can only control for the predisposition of and not the occurrence of disturbance within their forest stands. This system has been used for forest simulation frameworks, to assess stand predisposition to disturbances, including bark beetles (Temperli et al., 2020; Mathys et al. 2021). We developed the index in a similar manner creating a table in the form of a check-list of variables related to spruce bark beetle susceptibility (Table 1). The variables included in the index were identified through extensively reviewing literature on spruce bark beetles and discussing with experts. Eight variables were included in the index (Table 1). Each variable has been given a weighting, determining its importance in relation to the other

Table 1

Table of variables influencing forest stand susceptibility to spruce bark beetle. Columns contain the following information; Scale = describes if the variable influence susceptibility either on a larger scale (climate related) or on stand scale, Variable = the variable of interest. Relative weighting = its importance in relation to other variables, Indicators = thresholds or values indicating a change in risk, Relative score = strength of a variable at a certain indicator level, Motivation = reason for including a variable, References = literature supporting the motivation. *the variables volume of spruce, temperature and diameter all need to be larger than a certain threshold for the index to take any other value than zero (threshold: 0 m^3 for volume of spruce, 745 °Celsius for temperature and 20 cm for diameter). These initial requirements are written as functions (see Eqs. (3-5).

Scale	Variable	Relative weighting	Indicators	Relative score
Climate	Temperature (Temperature sum)	1.0	< 745 (< 1 generation)	*
			≥745, < 870 (1 generation in favourable conditions)	0.25
			≥870, < 1370 (1 generation)	0.5
			≥ 1370, < 1610 (2 generations in favourable conditions)	0.75
			≥ 1610 (2 generations)	1
Stand	Soil moisture	0.7	Dry	1
			Mesic	1
			Mesic-moist	0.8
			Moist	0.5
			Wet	0.2
Climate	Storm damage	0.3	Yes	1
			No	0
Stand	Volume of spruce	1.0	> 200m^3/ha	1
			150–200m^3/ha	0.8
			100–150m^3/ha	0.6
			50–100m^3/ha	0.4
			25–50m^3/ha	0.2
			>0 - 25m^3/ha	0.1
			0m^3/ha	*
Stand	Volume of birch	0.2	> 40m^3/ha	−1
			30–40m^3/ha	−0.8
			20–30m^3/ha	−0.6
			10–20m^3/ha	−0.4
			> 0–10m^3/ha	−0.2
			0m^3/ha	0
Stand	Stand density	0.4	≤ 0.4	0.4
			> 0.4, ≤ 0.6	0.2
			> 0.6 ,≤ 0.8	0.1
			> 0.8	0.3
Stand	Mean diameter (spruce)			
			≥20	*
			<20 cm	*
Stand (management)	Age structure	0.5	Even-aged	1.0
			Mostly even-aged	0.9
			Uneven-aged	0.5

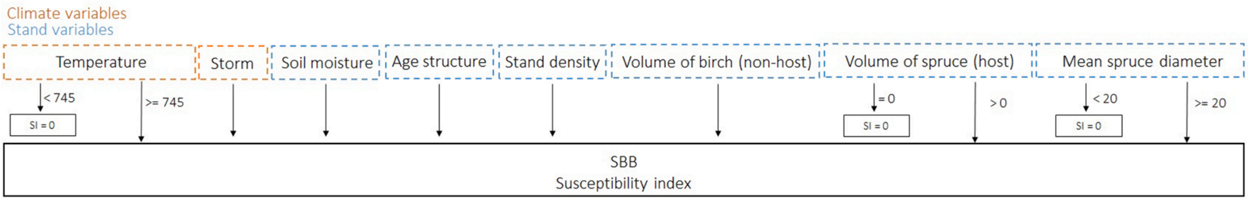

Fig. 1. Variables assumed to contribute to spruce bark beetle susceptibility included in the index, and if they are included as conditional or supportive variables. The conditional variables are volume of spruce, spruce diameter and temperature and if any of these variables are below a threshold the index (SI) will be zero, as susceptibility will be zero. The supporting variables contribute to the value of the index based on the indicator level of the variable (Tables S2-S8). Note that a variable can be both conditional and supportive. Colours denote if the variable is a climate variable (orange) or stand variable (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

variables (Table S1). The weighting of a variable was assigned based on following four steps; (*i*) the importance of the variable for spruce bark beetle susceptibility (variables determining beetle development directly have been given a higher weight), (*ii*) the amount of studies supporting the connection between the variable and spruce bark beetle susceptibility (variables with more empirical evidence have been given a higher weight), (*iii*) the unanimity of the findings (variables for which the outcome of studies are similar have been given a higher weight) and (*iv*) the occurrence of additional factors that could influence the uncertainty around the connection between the variable and susceptibility (variables were e.g. forestry practices influences strength of the relationship has been given a lower weight).Additionally, each variable is split into indicator levels, where every level corresponds to a score, which describes the susceptibility associated with that level of that variable (Tables S2-S8). The contribution of a variable to susceptibility is determined by the score multiplied by the weighting. Subsequently all variables are summed, providing a susceptibility index value (see description of calculation for details). The susceptibility index is a relative value, describing stand predisposition to spruce bark beetle, and can be used to compare different stands, or the same stand under different management and climate scenarios. The index is not designed to predict or estimate bark beetle damage, but to provide a measure of the extent to which a stand would suffer damage if exposed to bark beetles. The next paragraph describes all variables: 1) their contribution to spruce bark beetle susceptibility, 2) their implementation in the index and 3) the evidence underlying the weighting of their contribution to the index. We implemented the index in the forest decision support system Heureka (Wikström et al., 2011) version 2.18. The Heureka system is based on empirical growth and yield models and is widely used in Sweden, and simulations are run in five-year time steps (Fahlvik et al., 2014). By implementing the index in Heureka, users can simulate forest development over time and under different management alternatives to assess how spruce bark beetle susceptibility of e.g. forest stands is affected. Similar frameworks have been used in other forest simulation programs for this purpose (Temperli et al., 2020; Methys et al., 2021).

Description of susceptibility index calculations

For each stand, a unique susceptibility index is calculated, based on the value of the eight variables included in the index (Table 1). Three initial requirements need to be fulfilled for the index to take any other value than zero. 1) The volume of spruce needs to be larger than 0 m^3, 2) the temperature sum needs to be equal to or larger than 745 °Celsius (fulfilling the temperature requirement for one generation of spruce bark beetle to be completed) and 3) the mean tree diameter at stand level needs to be equal to or larger than 20 cm. When those requirements are fulfilled, the index will be calculated based on all eight variables. Each variable, except mean diameter, has a weighting (its relative importance compared with other variables) (Table S1) and a number of indicators (i.e. levels that the variable can take). Each indicator is associated with a score that is related to how the susceptibility increases or decreases with the indicator (all indicators and associated scores are presented in the Supplementary material S1; Tables S2 to S8). The contribution of each variable to the susceptibility value is calculated by multiplying the weighting of the variable with the score of the variable. All obtained values for each of the eight variables are summed to a stand level susceptibility index (Eq. (2)). The higher the index the higher the susceptibility. Below follows a step-by-step description of how the index is calculated

1 If the volume of spruce is zero, the susceptibility index will be zero, else move to point 2 (Eq. (3))
2 If the basal-area weighted mean diameter of spruce is $<$ 20 cm, the susceptibility index will be zero, else move to point 3 (Eq. (4)).
3 If the temperature sum is $<$ 745, the susceptibility index will be zero else move to point 4 (Eq. (5))
4 If the volume of spruce is $>$ 0, mean diameter of spruce $>$ 20 cm, and the temperature sum $\geq$ 745 the indicator level is obtained or calculated for each variable (a-g). Each indicator level corresponds to a score, which will be multiplied with the weighting of the variable to calculate the susceptibility value for each variable (Tables S1-S8) (Eq. (1)).
   a Volume spruce
   b Volume birch
   c Soil moisture
   d Temperature sum
   e Stand density
   f Age structure
   g Storm occurrence

$$Value_{variable\ i} = Weighting_{variable\ i} \times Score_{variabel\ i} \tag{1}$$

5 All variables values are summed to provide a susceptibility index (Eq. (2)). The index can obtain values within the range of 0 and 3.66 and higher values corresponds to higher susceptibility.

$$SI = \sum_{i=1}^{number\ of\ variabes} Value_{variable\ i} \tag{2}$$

Description of variables

Volume of spruce

Spruce bark beetles are specialist insects dependant on mature spruce for their development. If a stand has a volume of spruce that is zero, the susceptibility of that stand will be zero (Eq. (3)). Observations during a spruce bark beetle outbreak demonstrated increased bark beetle attack with increasing volume ($m^3 \times ha^{-1}$) of spruce (Kärvemo et al., 2016,) and a positive relationship between the volume of salvage logging and the volume of spruce has been shown (Netherer et al., 2019). Moreover, studies have reported positive relationships between tree mortality and proportion of spruce (Netherer and Nopp-Mayr 2005, Overbeck & Schmidt 2012). Spruce volume has been divided into six indicator levels, with an increasing score with increasing volumes. The range of each indicator level is based on Kärvemo et al., 2016 (Table S2). As occurrence of host tree is of critical importance to spruce bark beetle development this variable has been given a weighting of 1 (highest possible weighting). The choice of setting the weighting for spruce to 1 is also that can be used as a baseline when establishing the weightings of the other variables. Spruce volume can be directly obtained in Heureka on stand level.

%

$$If\ \left(Volume_{spruce} = 0\right)\ \{SI = 0\} \quad (3)$$

Spruce diameter

spruce bark beetle are almost exclusively found in trees with a diameter of at least 20 cm (Lekander 1972, Göthlin et al., 2000), most likely because the inner bark is not thick enough to create sufficient space for spruce bark beetle in smaller trees. Kärvemo et al. (2014b) measured the diameters of 20 000 infested wind-felled spruces and those ranged between 22 and 45 cm in diameter, however we have not identified any studies assessing the range of infested standing trees nor have we found any studies exploring the relationship between colonisation and developmental success with increasing diameter. Therefore, we decided to set a minimum diameter and include it as a binary function (Eq. (4)). We set the minimum average diameter at stand level to 20 cm. In Heureka, mean diameter (scaled for basal area) is provided, meaning that stands with a mean diameter of less than 20 cm will receive a susceptibility index of zero (Eq. (4)). Stands with mean diameters of less than 20 cm are relatively young, and low age has been associated with a lower risk of spruce bark beetle attack (Netherer 2003; Wermelinger 2004), providing an additional reason to include a diameter threshold. Additionally, mean stand diameter and volume of spruce is likely correlated and thus it may be misleading to incorporate both. Lastly, the use of mean diameter scaled for basal area may be problematic as a measurement as spruce bark beetle are dependant on the phloem (thickness of bark) and not the diameter of a tree trunk per se (a larger value would not necessarily mean more trees with thick enough bark) (Björklund and Lindgren 2010), providing yet another motivation for only including diameter as a binary variable.

$$If\ (diameter < 20)\ \{SI = 0\} \quad (4)$$

Temperature

Spruce bark beetles are ectotherms as thus dependant on certain temperatures or temperature sums to complete different steps in their life cycle (Wermelinger 2004). The voltinism (generations per year) of spruce bark beetle is regulated by temperature and with increasing latitude and altitude the number of generations per year decreases. Increased temperatures, as a result of climate change, are expected to alter these patterns and increase the likelihood of multiple generations in the Northern part of their distribution range (Jönsson et al., 2007, Jönsson et al., 2009, Romashkin et al., 2020). The risk of bark beetle attack and damage will increase with more generations per year and thus temperature is included in the susceptibility index as an important contributor to susceptibility. For each generation a certain temperature sum needs to be reached, with multiple generations this sum needs to be reached consecutively. Moreover, site microclimate affects the temperature sums required; the requirement is lower for sunny compared to shaded spots (Davidkova and Dolezal 2017). Based on this knowledge, we included several temperature sum (degree day) thresholds in the index: one generation under favourable conditions, one generation in all conditions, two generations in favourable conditions and two generations in all conditions. The temperature sum thresholds are based on Jönsson et al., 2009, Romashikin et al. 2020 and Fristscher and Schroeder 2022 (Table S5). If the temperature is too low for the completion of one generation the SI is set to zero (Eq. (5)). The weighting for temperature was set to 1, as we deemed it to be equally important for spruce bark beetle development as host tree availability. Moreover, as temperature contributes both to bark beetle development and potentially to tree stress (high temperatures leads to higher likelihood of drought) there is an additional motivation to give this variable a high weighting. Temperature sums per stand (calculated based on latitude and altitude) are available in Heureka, and change over time when using the climate module. Within the climate module, predicted temperature sums up to the year 2100 can be obtained for several future climate scenarios (RCP4.5, RCP8.5).

$$If\ (temperature\ sum < 745)\ \{SI = 0\} \quad (5)$$

Storm

The occurrence of storms increases the likelihood of bark beetle attacks due to creating a surplus of breeding material (i.e. wind-felled trees). The number of colonised wind-felled trees has been shown to be the most important predictor of tree mortality (Kärvemo et al., 2014b), availability of wind-felled trees was shown to be the main trigger of outbreaks in a study of a long-term data series from Sweden (Marini et al., 2013) and a study of data sets from 17 regions across Europe showed that availability of storm-felled trees is related to timber losses (Marini et al., 2017). Storms is therefore an important variable in terms of stand susceptibility, which should result in a high weighting of this variable. However, several factors made us lower the weighting of this variable. First, as storm is incorporated as a binary variable (occurrence of storm yes or no), there is no measure of storm severity and therefore the creation of breeding material is un-known. Moreover, with smaller storms there is usually enough time to remove felled trees before bark beetle infestation can occur, especially since most storms occur during winter. Thus, with regards to the uncertainty around removal rates as well as severity of storms, the weighting of the variable was set to be 0.3. Storm occurrence is a separate module attached to Heureka (based on Lagergren et al., 2012), in which occurrence of storms per stand can be obtained. If there has been at least one storm within a five-year time step the susceptibility index will be higher (Table S8).

Soil moisture

Soil moisture levels can indirectly affect bark beetles through effects on tree vigour, particularly during droughts. The occurrence of dry summers has been demonstrated to be a main outbreak driver in Central Europe (Ökland & Björnstad 2003, Marini et al., 2012) and drought stressed trees are more vulnerable to spruce bark beetle infestation (Netherer et al., 2015). Thus, one reasonable hypothesis is that forest on dry soils should be more vulnerable to spruce bark beetles due to higher risk of tree stress. In a study using pheromone trap data, the highest mean abundance of spruce bark beetle were found on rocky soils (Ökland and Björnstad 2003). Recent findings however suggest that acute, rather than chronic drought is important for bark beetle attack (Netherer et al., 2019) and thus another reasonable hypothesis is that trees on intermediately wet soils could be more susceptible to beetles, due to being less adapted to dry conditions, which may make them suffer more from acute drought stress during exceptionally warm/dry periods. Soil moisture level has been included in the index by associating each category of soil moisture (from wet to dry) with a score (Table S4). Based on the reasoning/knowledge outlined above, dry and mesic soils have been given equal scores, and thereafter the score decreases with increasing moisture. Due to the strong connection between soil moisture and tree health, as well as the comparably high number of studies exploring such patterns (e.g. Ökland and Björnstad 2003, Marini et al., 2012, Netherer et al., 2015), soil moisture has been given a rather high weighting (0.7). The weighting is set to be lower than volume of spruce and temperature as soil moisture level is not critical for spruce bark beetle development. In Heureka, soil moisture class is available at stand level.

Birch

The presence of birch trees has been hypothesised to have a negative effect on bark beetle susceptibility caused by deterring volatiles (Jactel et al., 2001; Zhang and Schlyter 2004). Kärvemo et al. (2016) found a negative relationship between spruce bark beetle colonisations and birch volume, supporting the hypothesis. However, in a different study, Kärvemo et al. (2014a) instead showed a positive effect of birch on spruce bark beetle attack up to volumes of 25 $m^3 \times ha^{-1}$, contradicting the hypothesis. Birch volume was included in the index with decreasing scores with increasing volume of birch. The low number of studies exploring this, in combination with the opposing findings (Cf. Kärvemo et al., 2016 and 2014a) made us decide to give the variable the lowest weighting (0.2). We did still include birch due to both the strength of the hypothesis and experimental studies showing that non-host volatiles do deter bark beetles (Zhang, 2003, Zhang and Schlyter 2004, Schiebe et al., 2012) alongside with the Kärvemo et al., 2016 study. Additionally, mixed stands, particularly conifer-broadleaves mixtures, are often more resilient to storms and droughts (Pardos et al., 2021) (which are two factors that increases spruce bark beetle susceptibility) and to specialist insect damage (Jactel and Brockerhoff 2007; Jactel et al., 2017). We believe volume of birch to be more important than what is reflected in the weighting but it is probably better to under than over estimate. Volume of birch is divided into six indicator levels, with a decreasing score with increasing volume. The range of each indicator level is based on Kärvemo et al., 2016 (Table S3). Volume of birch can be directly obtained in Heureka on stand level

Stand density

Stand density and crown cover can affect bark beetles through two different processes. A more open stand should let through more sunlight, which should contribute to more favourable micro climates (Netherer 2003; Kautz et al., 2013). However, a very dense stand should decrease tree vigour subsequently making trees more vulnerable to attack (Netherer 2003). Thus, open and dense stands should be of higher risk than intermediate ones. Stand density is included in the index in such a way that a higher value is given to open and dense stands, and a lower do intermediate stands (Table S6). The weighting of this variable is set rather low as it affects spruce bark beetle development indirectly (through sun exposure and tree stress) and since few studies have looked into this. The density of a stand is calculated according to the standard in the Swedish National Forest inventory using basal area and mean height (RIS Fältinstruktion, 2021), which are obtained per stand in Heureka. Density is expressed as a unitless relative value, calculated as ratio between the volume of the stand, compared to the volume that would be optimal to harness the wood production potential of the site. This way of describing stand density incorporates tree vigour, as a stand with a high value probably has a denser stand than would be optimal considering its productivity. Stressed trees have higher susceptibility than healthy trees.

Age structure

The age structure of the stand could affect spruce bark beetle through (i) decreased availability of trees of the right age (proposed by Klapwijk et al., 2016), (ii) lower probability of wind-throw (Shorohova et al., 2008), and (iii) increased predator:prey ratio due to increased variability of substrate (proposed by Nevalainen 2017). We included three age structure categories in the index; even-aged, mostly even-aged and uneven-aged, and assigned a lower value to uneven-aged stands and higher to even-aged and mostly even-aged (Table S7). The weighting of this variable was set to be relatively low as its proposed importance is mainly based on theoretical reasoning (Table S1). Age structure category can be directly obtained in Heureka per stand. The reason to incorporate age structure but not age per se was that the effect of age on susceptibility is likely (at least partly) an indirect effect of host tree volume/diameter.

Simulations

We exemplify how the susceptibility index works and can be used by running simulations in Heureka. We simulated the susceptibility index for an area located in Asa in Southern Sweden (located 37 km North of Växjö, lat. 57°10′N, long. 14°47′E). The area consists of 751 stands with a total area of 2451 ha, of which 2445 ha is productive forest, with a mean stand age of 46 years. Of the total tree volume of the area 78% is spruce, 18% pine and 4% birch. In the forest management plan for the area, 64 ha of the forest was assigned to no management (NO), 13 ha to nature conservation management (NC), 22 ha to wood production-focused management with increased consideration to ecological values (PF), and 2347 ha (96%) to production-focused management with general levels of ecological consideration (PG). We ran the simulation using the *RegWise* module of Heureka. *RegWise* is a simulation model in which users can define management for different types of forests. The NO, NC and PF areas were managed in the same way in all scenarios: no management for NO, selection fellings in NC, management aimed at increasing the share of broadleaves combined with longer rotation periods in PF. For the PG area, we applied three scenarios.

Baseline scenario: Even-aged management focused on conifers, retaining 10% broadleaves in cleanings and thinnings, with the forest being available for harvest as soon as it has reached the minimum age limit set in the Swedish forestry legislation. Around 35% natural regeneration. Roughly 50% of the planted area planted with spruce, and 50% with pine

Longer rotation scenario: As baseline but with the minimum harvest age increased by 30%.

Mixed forest scenario: As baseline but retaining 40% broadleaves during cleanings and thinnings.

To simplify the simulations, we did not include storm damages (i.e. storms were not simulated) or any climate scenario. In the PG area, harvest levels are simulated to correspond to the net annual increment, if possible given the restrictions in minimum harvest age and guidelines for thinnings. We expect a higher index in the longer rotation scenarios, as the volume of spruce would increase with time and since more stands would reach the required minimum diameter. We expect a lower index in the mixed forest scenario since the total volume of spruce should be lower and the volume of birch higher (Klapwijk et al., 2016). We obtained and present four types of output from the simulations: 1) The area-weighted mean spruce bark beetle susceptibility index on property level, 2) the harvest volume (m^3) on property level, 3) the index variables (Fig. S1, supplementary material) on property level, and 4) the susceptibility index on individual stand level for four haphazardly chosen stands (referred to as stand A, B, C and D (Heureka specific stand code provided in the Supplementary information Table S9)), from 2020 to 2100, per five-year interval, for all three scenarios.

Results

How the value of the index changes with different levels of the variables and under different combinations of variables is demonstrated in figs. S2-S6 (supplementary material) and can be explored through this application: https://nordkvist.shinyapps.io/Index/ Simulations.

Mean susceptibility index

Figs. 2 shows the mean value of the index variables over time for the three scenarios. There is a general trend to a lower index value over time in all scenarios, caused by the initially high amount of spruce in Asa, and the subsequent decrease in spruce volume above 20 cm in diameter (Figs. S1). The longer rotation scenario results in a higher mean index value compared to both the baseline and mixed forest scenarios. The baseline and mixed scenarios are similar.

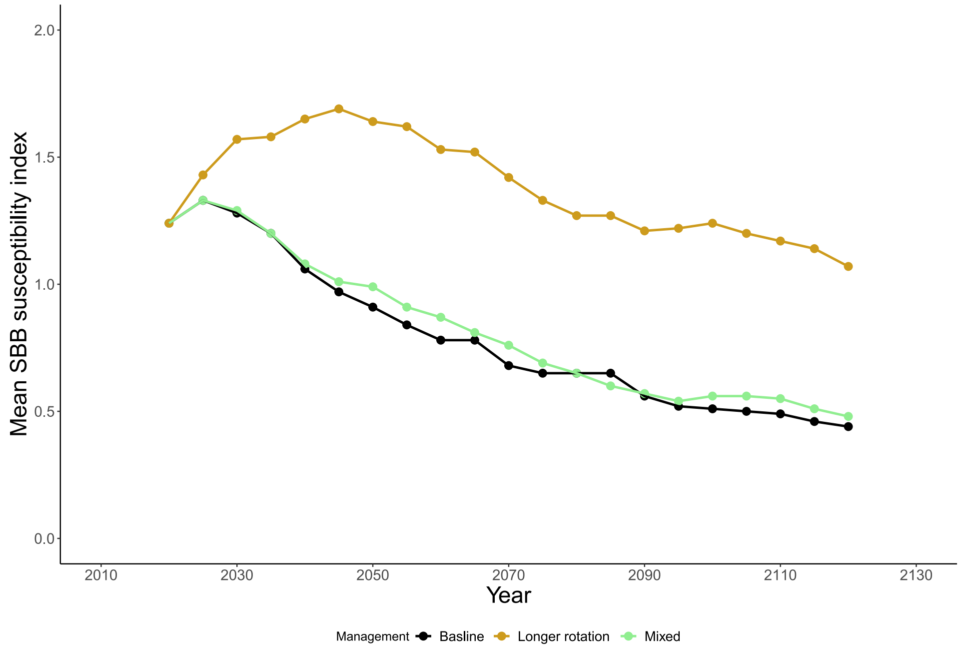

Fig. 2. The mean spruce bark beetle susceptibility index from 2020 to 2100, per five-year interval for the three management scenarios: baseline (black), longer rotations (brown) and mixed forest (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Harvest

The mean harvest volume is presented in Fig. 3 for the three management scenarios. Harvest is, for most of the time period, slightly higher in the baseline scenario compared to the longer rotation and mixed forest scenarios. Harvest is considerably lower in the longer rotation option during the first 15 years, due to a lack of forest available for final felling.

Stand level susceptibility index

The stand level index values for the four haphazardly chosen stands (A, B, C and D) are presented in Fig. 4. Depending on the initial stand characteristics and the development of the variables over time, the choice of management affect all stands differently. For stand C the susceptibility index is the same across time for all three scenarios. For stand A, B and D the longer rotation scenario has higher index values and more time points above zero. The mixed forest scenario has lower index

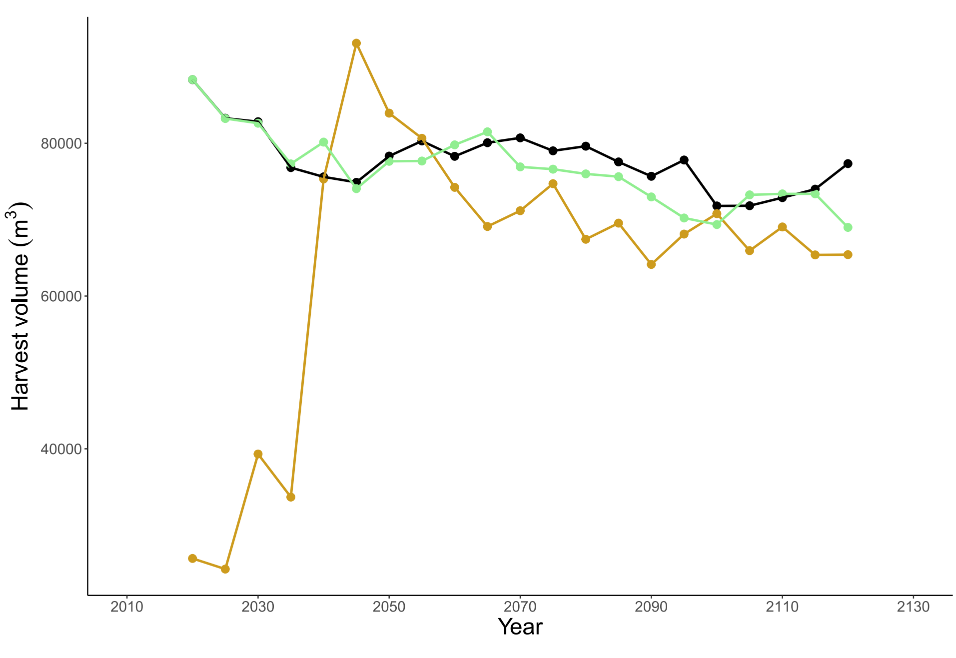

Fig. 3. The mean harvest (m^3) from 2020 to 2100, per five-year interval for the three management scenarios: baseline (black), longer rotations (brown) and mixed forest (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

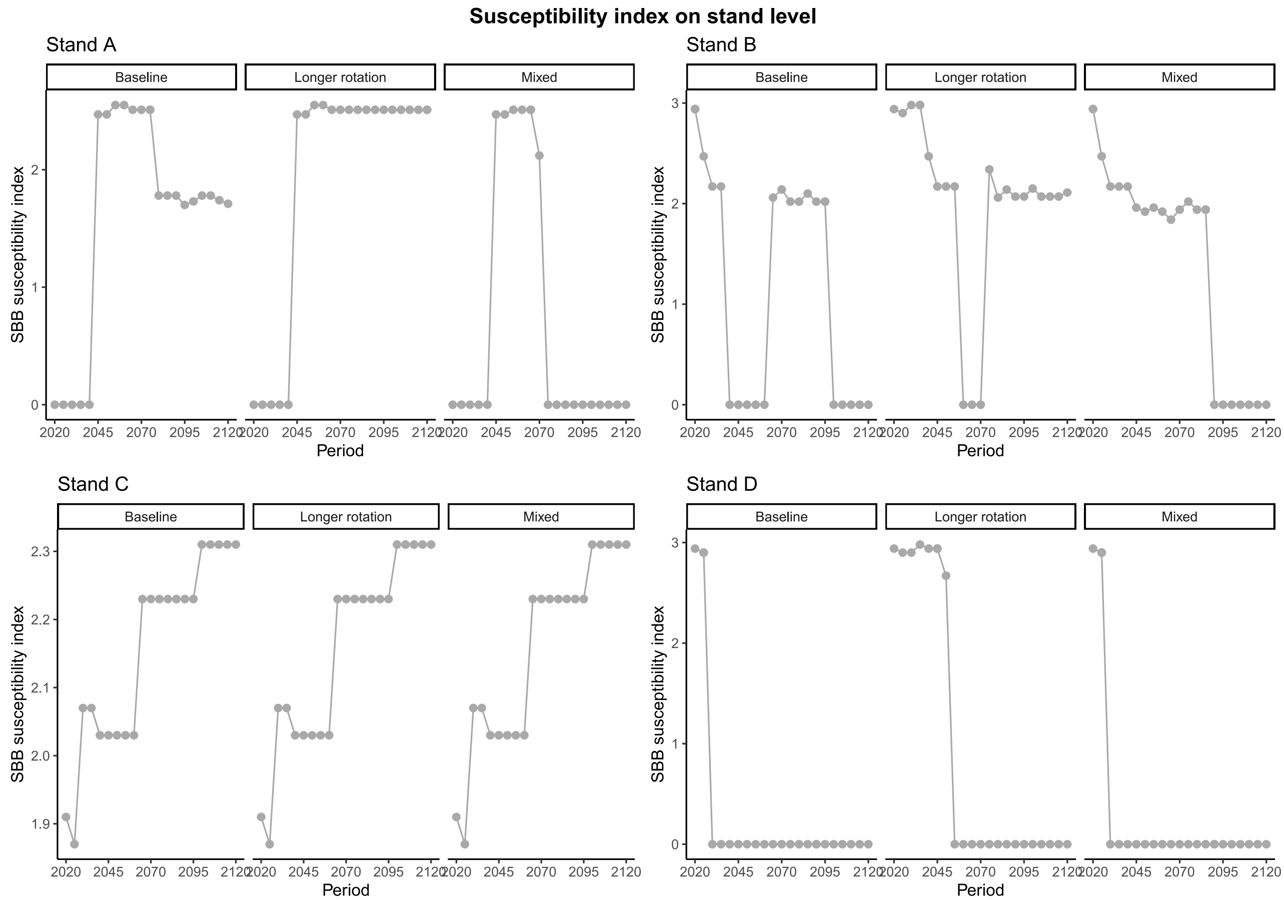

Fig. 4. The spruce bark beetle susceptibility index from 2020 to 2100, per five-year interval for four individual stands (A, B, C and D) for the three management scenarios: baseline, longer rotations and mixed forest.

values and fewer time points above zero in stand A compared with the baseline scenario, while the opposite is true for stand B.

Discussion

In this paper, we present a susceptibility index for spruce bark beetle implemented in a forest decision support system for the purpose of estimating the relative susceptibility of a stand to spruce bark beetle based on stand characteristics. The output of simulations, as presented here, can be used to evaluate stand and area level management decisions for different management and climate scenarios. The index combines ecological knowledge and theory and produces a relative measure of spruce bark beetle susceptibility based on eight variables. It is important to consider that the index value is relative, and of potential susceptibility but not a prediction of attack or an estimation of damage. Thus if a stand has a high value of susceptibility, it does not give any prediction about the likelihood of a stand to be attacked. The index is a description of stand predisposition to spruce bark beetle damage, the higher the index value the more susceptible a stand would be when or if it was exposed to bark beetles. We do believe that a relative value of the susceptibility of a stand is a valuable tool that will help to make decisions for a future where spruce bark beetle outbreaks are expected to become more frequent (Schelhaas *et al.* 2003; Seidl et al., 2008). The index includes several variables that can be considered in forest planning, such as choice of tree species in relation to stand soil moisture level. The index can therefore aid decision making at stand scale that could affect landscape level susceptibility as well, and in that way inform decision-making when it comes to forest health.

Currently the index is developed at stand level and does not consider landscape connectivity. In reality, stands are not isolated and stands nearby are very likely to affect susceptibility of a focal stand (Kärvemo et al., 2016). For example, higher spruce volume and diameter of storm-felled trees in the landscape (i.e. suitable stands) has been shown to increase tree mortality of a focal stand during an outbreak (Kärvemo et al., 2014b). At the same time, a stand may be more vulnerable when surrounded by stands unsuitable for spruce bark beetle, if the spruce bark beetle manages to locate it.

The index is as good as the information available used to formulate and weight the included variables. Increased understanding of the ecological context leading to spruce bark beetle outbreak is needed to fine-tune the index. One variable that would be important to incorporate in future versions of this index is drought. Water-stressed trees are more susceptible to spruce bark beetle attack (Netherer et al., 2015; Mathews *et al.* 2018) and drought is one of the drivers of spruce bark beetle outbreaks (Marini et al., 2012). Because of the close relationship between drought stress and tree level susceptibility to spruce bark beetle, including drought stress with a higher level of precision would improve the index. Moreover, the effect of temperature could be fine-tuned by including the effect of temperature on additional phenological factors. Increased temperature could lead to earlier and more aggregated swarming, more frequent sister broods and decreased winter mortality (Wermelinger 2004), effects that are all predicted to increase the risk of mass infestation (Jacoby et al., 2019). More experimental studies assessing these relationships would be useful. Lastly, the storm variable could be fine-tuned by including some kind prediction or estimation of storm severity or by instead characterising stand predisposition to storm and include that as a variable.

The inclusion, weightings and scores of the index variables are based on expert-understanding and experimental studies of the ecological relationships leading to spruce bark beetle outbreaks and landscape level attack patterns. However, if stands with a higher index are more prone to spruce bark beetle damage is yet to be tested. The next step in the process of index development should therefore be to use data gathered during an ongoing outbreak to validate it.

Simulations

The results of the simulation show how the index can be used to test how susceptibility differs under different management scenarios at stand level and at property level (Figs. 2 and 3). This will be useful for forest owners/practitioners as it provides a fast way of assessing different management options in relation to spruce bark beetle susceptibility.

The outcome of the simulation on property level demonstrates that in the longer rotation scenario the spruce bark beetle susceptibility index increases, compared with the baseline. This is in line with our expectations, as longer rotations result in higher volumes of spruce and more spruce with a diameter above 20 cm (Fig. S1). Contradictory to our expectations, there was no difference between the baseline and mixed scenarios. We believe that this is mainly an effect of volume of spruce with a diameter larger than 20 cm being very similar between the scenarios (Fig. S1). The outcome on stand level shows similar patterns as the outcome on property level but also clearly demonstrates that it varies from stand to stand and for some stands changing management might make no difference for spruce bark beetle susceptibility, suggesting that management planning relating to spruce bark beetle susceptibility should be considered on stand level. Moreover, on stand level it is clear that the mixed forest strategy can make a difference in susceptibility (Fig. 4). It also shows how the index value varies during different parts of the management cycle. We believe that our susceptibility index used in the simulation framework is a useful tool in forest management decision making, and can be used to highlight risk areas now or in future scenarios.

Author contributions

MJK and JE developed the idea. MN developed the risk index, with input from MJK and JE. JE ran the simulations in Heureka. MN wrote the manuscript. All authors contributed to revisions of the manuscript.

Declaration of Competing Interest

The authors have no competing interests to declare

Data availability

data included in submission as excel file

Acknowledgments

We greatly appreciate the valuable feedback of the following expert who supported the development of the spruce bark beetle index with their knowledge: Martin Schroeder. The research was partly funded by Swedish Forest Agency (Skogsstyrelsen 2020/1330), and partly by the Mistra foundation (Grant number: DIA 2017/14#6″, Project title: Mistra Digital Forest.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2022.100364.

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