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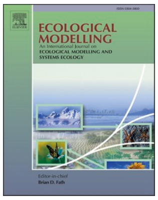

Management approaches in decision support systems to mitigate the risk of natural disturbances in European temperate and boreal forests –a review

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ABSTRACT

Natural disturbances such as windthrow, bark beetle outbreaks, root rot, wildfire and snow or ice damage are increasingly affecting temperate and boreal forests under climate change, creating a need for adaptive management to maintain forest resilience and productivity. Decision Support Systems (DSSs) integrating disturbance dynamics can support managers in adjusting management to these evolving risks. This review synthesizes management recommendations derived from DSSs incorporating natural disturbance models in European temperate and boreal forests. The results reveal that most DSSs rely on simulation models applied at strategic spatial and temporal scales, with particular emphasis on windthrow risk, bark beetle outbreak, and root rot damage. Conifer-dominated, even-aged plantations appear most vulnerable to multiple disturbances, whereas mixed-species stands show greater resilience. Simulations underscore that proactive strategies, such as shortening rotation length, species mixing, and targeted thinning, can reduce disturbance risks, but compromise timber revenues and other ecosystem services. Reactive strategies, including salvage logging and sanitary cuttings, address immediate damage but offer limited long-term mitigation. Optimization methods can help mitigate the trade-offs between profitability and forest resilience by minimizing disturbance risk and maximizing economic outcomes. While several DSSs can integrate single disturbances, only few DSSs can simulate interactions among disturbance models and climate scenarios. Complex data requirements constrain DSS application for operational forest management, restricting their use to researchers. Future DSS development should prioritize simple, applicable and accessible solutions while integrating advanced models capable of addressing diverse disturbance regimes. By leveraging advanced DSSs, forest managers can enhance forest resilience amid increasing climate-driven disturbance pressures.

1. Introduction

Natural disturbances in forests have increased globally in recent decades and are projected to increase further under climate change (Ellis et al., 2022; Patacca et al., 2023, Altman et al., 2024). These changes in the natural disturbance regime have profound impacts on forests and their ecosystem functions and services (Lecina-Diaz et al., 2024). Natural disturbances can, for example, cause substantial economic losses (Knoke et al, 2021; Hahn et al., 2021) and reduce the ability of forest to act as a carbon sink (Korosuo et al., 2023), thus further exacerbating climate change. For forest managers, natural disturbances add considerable planning uncertainty and raise the need for management approaches and planning tools which take into account disturbance risks (Daniel et al, 2017; Nikinmaa et al., 2024). The use of adaptive forest management approaches can mitigate the risk and overall damage caused by a range of disturbances. On one hand, forests can be proactively managed with an aim to increase their resilience to disturbances by increasing the diversity of species and structural elements of the forest. On the other hand, forests can be managed reactively after disturbance events to minimize the impacts and mitigate the potential

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cascading damages (Thom, 2023). To manage immediate risks, decision makers can use a variety of methods to take decisions under risk and uncertainty (Eyvindson and Kangas, 2018). To be effective these approaches require information on the complex interactive effects of climate, natural disturbances and management on the forest ecosystem (e.g., Repo et al., 2024).

To enable quantitative assessment of disturbances, a variety of Forest Natural Disturbances Models (FNDMs) have been developed. An early review of FNDMs has explored the taxonomy of approaches to modelling single disturbance events and the impact of disturbance regimes in forest ecosystems (Seidl et al., 2011). More recent and extensive reviews about FNDMs have focused on specific problems: Sturtevant and Fortin (2021) examined the effects of interactions of several FNDMs on forest dynamics, while Romeiro et al. (2022) analyzed how climate change is dealt with in FNDM predictions. Answering how disturbances interact and are impacted by climate change is crucial, as natural disturbances affect forest dynamics in combination as one disturbance can increase the susceptibility of the forest to other disturbances. This positive feedback loop leads to an increase in the disturbance severity, fostered by altered climatic patterns (Masson-Delmotte et al., 2021; Patacca et al., 2023).

Disturbances change the forest state (i.e., structure, composition, and functions) differently at specific stages of the forest succession (Peng, 2000). For this reason, FNDMs integrate eco-physiological processes acting at different spatial and temporal scales (Seidl et al., 2011). Therefore, in principle, FNDMs should include predictors spanning these scales. FNDMs typically include climate data (Romeiro et al., 2022) and damage frequency and intensity across multiple years (e.g., Lausch et al., 2013). This requires integration of predicted climatic variables across the entire planning horizon to enable forecasting of scenarios using model-driven forest decision support systems (DSSs). These predictors can be integrated with stand-level forest variables derived from management plans applied in a short temporal frame of few years or from large scale inventories (e.g., national forest inventories) reporting repeated measurements from multiple decades.

A comparative review by Segura et al. (2014) noted that FNDMs have been implemented in a selection of DSSs using a variety of methodological approaches for multiple uses in forest management. Integrating FNDMs in DSSs allows for the possibility to simulate the effects of disturbances under alternative management regimes (Triviño et al., 2023). This can aid forest planners to estimate the potential damage caused by disturbances and evaluate how much of this damage can be mitigated with adaptive management (Schafellner and Möller, 2022). Using DSS the simulated scenarios can be connected with optimization approaches to enable planners to develop management plans that minimize the risk of disturbance while maximizing the even-flow of timber (c.f., Eyvindson et al., 2024), biodiversity and other ecosystem services.

Disturbance, as discrete event in time inducing forest damage, can appear at various temporal scales, ranging from immediate to delayed extending over decades. Damages caused by wind (“windthrow”) and fire take place immediately. Damages caused by bark beetle outbreak occur quickly, but the damages are readily observed after one to two growing seasons after the attack. Other damages, like root rot, can develop slowly, taking decades before the damage can be noticed, for instance during harvesting actions. Therefore, the approaches to conduct adaptive forest management varies according to the timescales of the disturbances.

There is a large body of literature describing the relationship between climate, forest characteristics and vulnerability of trees to wind and management. Forest companies, public agencies and research institutions have expressed the need for actionable information that could facilitate the practical application of measures to mitigate forest disturbances (Nikinmaa et al., 2024) and the need for more DSSs integrating all these aspects (de Pellegrin Llorente et al., 2023). For example, Blennow and Sallnäs (2002) have showed that forest owners in southern Sweden rank the risk of wind damage highly, but they generally do not know how to change their forest management to reduce this risk. A recent review about sources of uncertainty in forest planning (de Pellegrin Llorente et al., 2023) has highlighted that only few forest DSSs implementing FNDMs embed estimates of the uncertainty of natural disturbances (e.g., the YAFO model, Härtl et al., 2013), even though this information could inform planners on the likelihood that disturbances affect forests. For instance, forest planners would be likely to take less uncertain and risk-prone management decisions if they could compare the effects of natural disturbances on the forest capacity to supply ecosystem goods and services under alternative adaptive management options (Kangas et al., 2018).

While several individual studies exist where FNDMs have been linked with DSSs, we still lack a comprehensive synthesis that clarifies what types of DSSs embedding FNDMs are available for forest owners and managers and which kind of disturbance-related management decisions they can reliably inform. Closing this gap is critical for improving our ability to forecast and prepare for the intensifying impacts of climate-change induced disturbances on the long-term provision of biodiversity and ecosystem services in temperate and boreal forests (Hanewinkel et al., 2010; Tognetti, 2017; Kangas et al., 2018). For this reason, we compiled a review summarizing the existing knowledge on the types of decision support systems available for decision makers to mitigate the typical disturbances occurring in the European temperate and boreal zones including windthrow, bark beetles, fire, root rot and ice/snow breakage. We then grouped DSS by disturbance agents, by their approach based either on simulation and/or on optimization and by their spatial and temporal simulation horizon. Finally, we evaluated the impacts predicted with DSSs of the most applied proactive and reactive management strategies on the disturbance effect and risk.

2. Methods

The articles (written in English) included in this review were selected by means of a literature search conducted in Web of Science and Google Scholar by using a combination of keywords for each disturbance agent: (“root rot” OR “heterobasidion” OR “windthrow” OR “wind damage” OR “bark beetle” OR “typographus” OR “snow damage” OR “ice damage” OR “fires”). For facilitating comparability, we referred only to the natural disturbance agents included in the previous literature search over the links between risks and climate change by Romeiro et al. (2022). “Drought” was not explicitly considered as a disturbance agent, as it was usually embedded in the weather component of the DSS directly affecting forest processes and was not treated with independent models like other disturbances. Nevertheless, “drought” was included among the studies where it appeared together with other disturbance agents. “Browsing” was also not considered in the review given its limited implementation in DSSs. We incorporated in the search FNDMs and DSSs including key terms related to these aspects: AND (“model*”) AND (“forest planning” OR (“decision support system*” OR “DSS” OR "forest simulator*")). Then we considered the type of forest for which the research was conducted: AND (“temperate” OR “boreal”). Additional papers were identified throughout the reviewing process by referring to pertinent studies that were cited in the reviewed literature making use of a “snowballing” method. We considered studies in the years ́ range 1996–2024 primarily conducted in Europe.

We classified how FNDMs have been implemented only in model-driven DSSs (classified *sensu* Power, 2002) able to forecast future forest development. Therefore, we excluded all the Data-Driven DSS that support only visualization of maps of potential disturbance occurrence and/or make use of these maps to predict risk probability. We based our classification on the disturbance agent, the number of managed units (number of stands), the spatial scale (in hectares, ha) and the temporal scale (in three categories, operational (days to months), tactical (2–10 years), strategic (>10 years)) at which simulations were conducted. We also evaluated the type of forest (hemiboreal, boreal, temperate), the dominant tree species, the prevalent strategy of management applied (either proactive or reactive), the eventual optimization technique applied to maximize objectives, if the approach is implicitly (i.e. as an optimization objective) or explicitly (i.e. in the problem formulation in stochastic programming or when deciding about the optimal rotation time) dealing with the risk, how the risk is defined (i.e., as disturbance probability or damage intensity) and the sources of uncertainty accounted for (e.g., climate scenarios) or unaddressed in the FNDMs and DSSs (e.g., climate-insensitive decomposition rates).

A total of 337 papers in the field of forest natural disturbances responding to the terms of the literature search were initially filtered, from which we screened 66 peer-reviewed articles (see Appendix A. Supplementary data for a complete list) where FNDMs have been implemented in DSSs in western (Belgium, France, Ireland, Netherlands, United Kingdom), central (Austria, Czech Republic, Germany, Slovakia, Switzerland) and northern (Denmark, Finland, Norway, Sweden) Europe between 1997 and 2024 (Fig. 1). Most of the studies were conducted in Finland (23), Sweden (12), Germany (5), Austria (3) and Slovakia (3), while other countries reported one or two case studies each.

The total number of studies incorporating FNDMs in DSSs increased from 1997 to 2009–2010, the years when it peaked (9 studies), and then had a second increment in the period 2015–2020, with a second peak in 2017 (10 studies) (Fig. 1). As shown in Fig. 1, the overall increase in the number of studies was mainly driven by windthrow, with bark beetle and root rot contributing to a lesser extent, while wildfire and snow or ice played only a marginal role.

The trend in the cumulative percentage of the FNDMs-DSSs studies alternated periods of slow increase (only by +13.6 % and +13.6 % in the periods 1997–2005 and 2011–2015, respectively) to periods of fast increase (by +28.8 % and +30.3 % in the periods 2007–2010 and 2016–2024, respectively) (Fig. 2).

Most (64, 66.7 % of the total) of the studies simulated a single disturbance, with eight studies (8.3 %) including an interaction between two disturbances and three studies (3.1 %) the interaction between three disturbances. Specifically, thirty-three studies (34.4 %) included only damage or risk from windthrow, nine (9.4 %) from root rot, i.e., from *Heterobasidion* spp., twelve (12.5 %) from bark beetle, i.e., from *Ips typographus*, seven (7.3 %) from wildfire, three (3.1 %) from snow or ice. The interaction between windthrow and bark beetle was included in six studies (6.3 %), while single separate studies were conducted for the interaction between windthrow and root rot (1.0 %) and between windthrow and snow damage (1.0 %). Finally, two studies (2.1 %) included the interaction among windthrow, bark beetles and root rot and one (1.0 %) the interaction between drought, windthrow and bark beetles.

3. Forecasting decision support systems for managing forests for natural disturbances

3.1. Impact of forest management on wind damage risk

3.1.1. Forests and management scenarios under windthrow

Almost all the studies implementing windthrow models in DSSs simulated growth of coniferous and deciduous plantation forests. Specifically, the growth of the following tree species was simulated: spruce (Norway spruce, *Picea abies*; black spruce, *P. mariana*; Sitka spruce, *P. sitchensis*), pine (Scots pine, *Pinus sylvestris*; jack pine, *P. banksiana*; lodgepole pine, *P. contorta*; red pine, *P. resinosa*; white pine, *P. strobus*) and birch (various *Betula* species). The simplified vertical structure of these cultivated forests makes them particularly susceptible to windthrow (Schelhaas et al., 2003). In particular, the shallow-rooted Norway spruce, the most simulated species, has a low susceptibility to wind as young plant but it is deeply affected as it approaches high height (Wohlgemuth et al., 2022a). In the boreal context, the effects of windthrow were simulated in pure spruce plantations or in admixtures of spruce with pine and birch. Other less represented simulated coniferous and deciduous species were fir (Douglas fir, *Pseudotsuga menziesii*; balsam fir, *Abies balsamea*; silver fir, *A. alba*) with other softwood species and European beech (*Fagus sylvatica*) with other hardwood species. The lower representation of broadleaved deciduous trees than coniferous trees in simulation studies is related with their lower susceptibility to winter storms, as the shedding of leaves results in a proportionally smaller exposed surface area (Wohlgemuth et al., 2022a). Most of the simulations were conducted at the spatial scale of the whole forest landscape and at the strategic temporal scale of one to two rotation periods. This long spatio-temporal planning horizon is compatible with

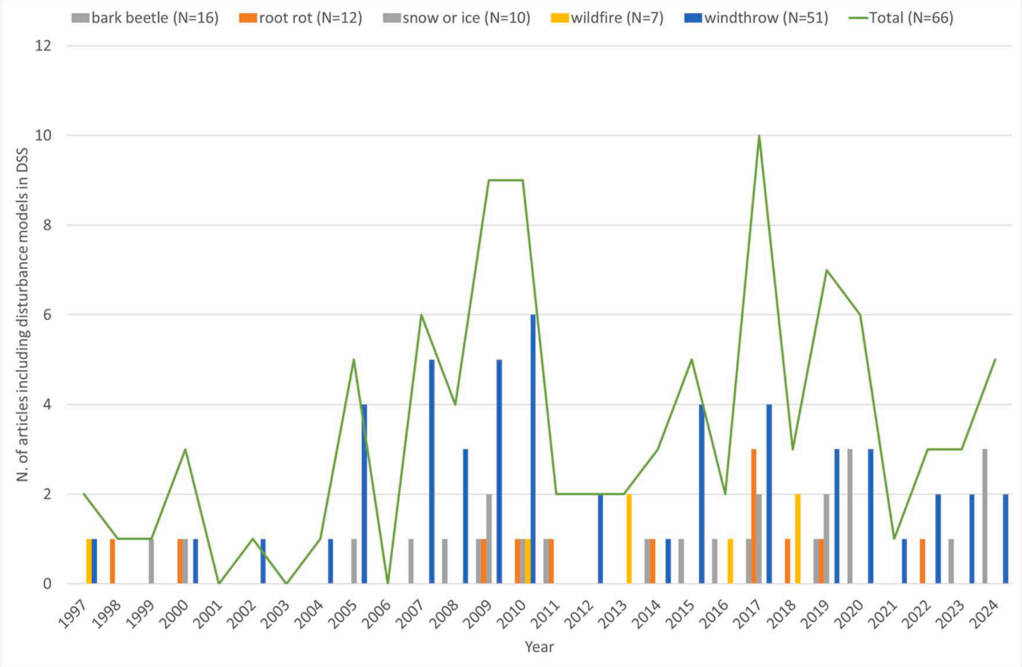

Fig. 1. Yearly number of studies including single forest natural disturbance models in Decision Support Systems by disturbance type (data from western, central, and northern European countries). Disturbances reported within the same article are counted as separate studies.

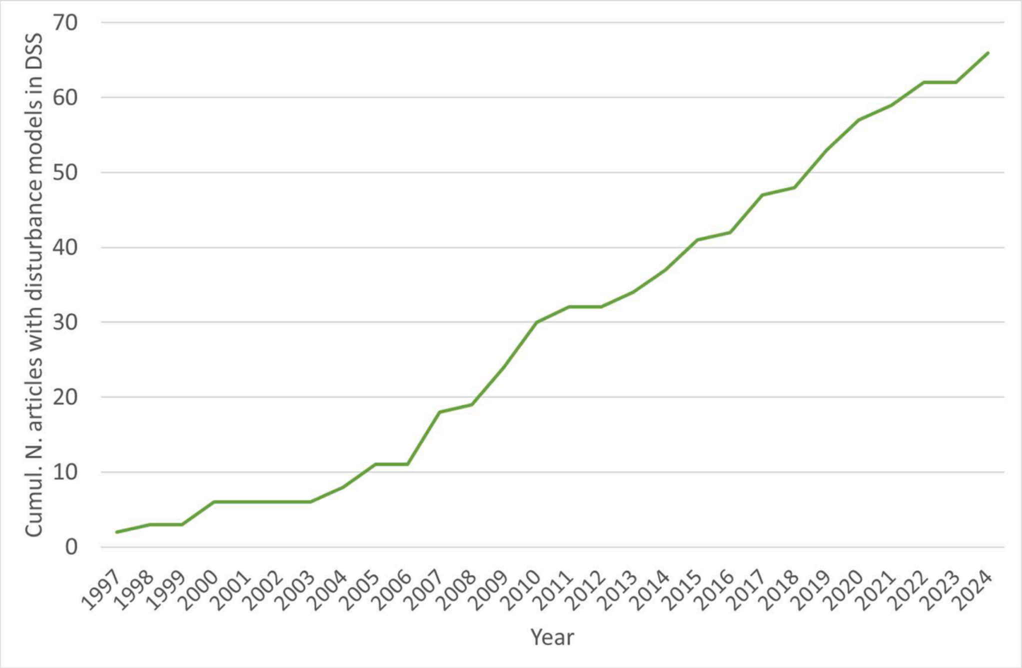

Fig. 2. Cumulative yearly number of studies where natural disturbance models were incorporated in Decision Support Systems (N=66, total reported for western, central, and northern European countries).

the long-time span at which windthrow events take place and has practical relevance for predicting the landscape-level consequences of storm damage.

The management practices most often simulated by the DSSs for the plantation forests were even-aged rotation forestry based on thinning followed either by shelterwood or clearcutting. The reason is that these are the practices that make the forest stands more susceptible to windthrow: specifically, thinning from above removes the dominant trees from the stands, while clear-cutting suddenly exposes stand edges to windthrows (Wohlgemuth et al., 2022a). Proactive management strategies that were compared to ordinary rotation forestry to simulate the increased or reduced wind damage risk included changes in rotation length, timing and intensity of thinning, regeneration with broadleaves, tree cutting selection. Specific management strategies adopted a combination of practices fulfilling the wood demand from bioenergy and bioeconomy (Lundholm et al., 2020) or reacting to increasing disturbances (Riguelle et al., 2015). Ordinary management practices (i.e., rotation forestry or Continuous Cover Forestry (CCF)) were used to evaluate the effect of topography on wind speed (Ruotsalainen et al., 2022).

DSSs simulated the impact of wind damage and storm events on the forests under current and future climatic conditions, simulating changes in temperature and precipitation patterns driven by specific combinations of general circulation models and emission scenarios (Kellomäki and Väisänen, 1997) and increased carbon dioxide concentration (Blennow et al., 2010a,K. b; Jönsson et al., 2015). Subramanian et al. (2016) simulated scenarios evaluating the potential of replacing spruce with hybrid larch and birch with hybrid aspen and beech to mitigate windthrow risk and boost tree growth and revenues. To explore the impact of proactive management Díaz-Yáñez et al. (2019) simulated the impact of wind damage on shorter rotations.

3.1.2. *Management recommendations based on simulation of windthrow risk*

Simulation studies analyzed the effect of management strategy under the risk of windthrow. For instance, the effect of varying rotation length has often been simulated to evaluate the risk of windthrow. In several studies, Shortening the Rotation Length (SRL) has proven effective in reducing windthrow disturbances (Thiele et al., 2017; Zimová et al., 2020). SRL has been found as a potential approach to mitigate the impacts of windthrow on timber revenues (Peltola et al., 2010), even though it has undesired consequences on other ecosystem services and biodiversity (Subramanian et al., 2016; Potterf et al., 2024). SRL results in a rotation where stands are thinned less in favor of anticipated clear-felling operations. On the other hand, Extending the Rotation Length (ERL) could be implemented in stands providing wind shelter for other stands (Zubizarreta-Gerendiain et al., 2017).

In addition to the estate or landscape level recommendations, simulations can be used to produce stand-level recommendations. For instance, Schelhaas (2008) reports that harvesting only the tallest trees contributes to stand stabilization against windthrow, lowers the mean stand height, the canopy height differences among adjacent stands, and the height–diameter (h/d) ratios. In CCF cutting concentrates on trees with larger diameter resulting in higher h/d ratios and thus higher susceptibility to windthrow risk (Panferov et al., 2010; Potterf et al., 2022; Ruotsalainen et al., 2022). In contrast to CCF, rotation forestry reduces windthrow risk by lowering tree age and height (Kellomäki and Väisänen, 1997). A combination of both management approaches (rotation forestry and CCF) could provide an efficient way to reduce the amount of wind-exposed timber volume and increase species habitat (Potterf et al., 2024).

In the long run, the simulation approaches can be used to make recommendations on which tree species to plant for the future generations of trees. In temperate and boreal plantations, increasing the share of Norway spruce compared to Scots pine over the forest landscape increases disturbance-related damage (Potterf et al., 2022). Instead, there is a mixed evidence towards the effect of deciduous species such as birch (*Betula* spp.) on wind risk: Zeng et al. (2010) have shown significantly lower risk to wind damage in boreal conditions since most storms occur from late autumn to early spring when deciduous species have no leaves and consequently experience much less wind loading (Zeng et al., 2010); on the other hand, Repo et al. (2024) adaptation scenarios replacing spruce with deciduous trees increased the wind risk.

3.1.3. Management recommendations based on optimization of timber and windthrow risk

Optimization can be used to explore the consequences of minimizing or maximizing the risk of windthrow for the potential supply of timber at landscape level. Eyvindson et al. (2024) explicitly optimized the management in the forest landscape to deal with immediate wind risk. The objective of management was to either maximize the expected Net Present Value (NPV) of the future incomes or to minimize the conditional value-at-risk, i.e. minimize the expected losses of windthrow events, with or without constraints regarding future harvest levels. Windthrow risk is modeled using scenarios based on windspeed frequency and intensity, with damage occurring when windspeed surpasses the stand's critical threshold. Depending on the objectives of planning, the resulting management recommendations can be either shortening or lengthening (in a case of harvest level constraints) the optimal rotation in each stand. There are limitations from this approach, as the scenarios are pre-defined, they do not account for the nearby gaps in the forest structure and cannot be used for planning the locations of harvest to minimize the gaps. Moreover, as the selected scenarios are not representative (i.e. random sample from among all possible combinations), the optimization may not recommend the truly optimal rotation lengths.

Another approach to use optimization is to include risk or indicators of risk as one objective among multiple other objectives. For instance, Zubizarreta-Gerendiain et al. (2017) and Ruotsalainen et al. (2022) maximized an additive utility function, where the difference in height between adjacent stands, derived both from topography and tree height, was one of the objectives that could be either minimized or maximized to minimize or maximize the risk of windthrow. The height differences between the stands could be weighted through various measures, for example using the mean elevation of the stands. Zeng et al. (2007a, c) maximized an additive utility function where the windthrow risk was described with the percentage of vulnerable edge between stands in each period or by the number and area of vulnerable stands. The edge was considered vulnerable when the critical wind speed needed to cause damage was less than 20m/s. This approach can be used in proactive planning at the landscape level, to minimize the risk levels in future by planning the locations of the current harvests (Ruotsalainen et al., 2022; Zeng et al 2007b,c).

In the boreal forest, the level of risk of wind damage at the landscape level is significantly affected by the presence of gaps and old stands in the forest, and the specific location of the stand in the landscape can change its exposure to wind damage (Kulha et al., 2024; Thürig et al., 2005; Zeng et al., 2010). On the other hand, species composition (Scots pine and/or Norway spruce) has a much smaller impact on the risk of damage.

Applying approaches that strive to minimize windthrow risk will negatively impact the expected NPV. However, the expected loss in NPV may be compensated by lower risk to the NPV due to the forest management (Zubizarreta-Gerendiain et al., 2017). An optimal policy to minimize windthrow thus weights the benefits of clear-cutting the stands at an early age (with smaller but earlier revenues from harvest, lower risk of wind damage, and less shelter provided by the stands) against the benefits of delaying the clear cuttings (with larger but later revenues from harvest, higher risk of wind damage, and more shelter provided by the stands) (Thürig et al., 2005). When using optimization to minimize the expected losses (Eyvindson et al., 2024), the economic profitability of the risk management is accounted for in the analysis but requires preference information regarding how much risk the decision maker is willing to take.

3.2. Impact of forest management and climate change on bark beetle damage risk

3.2.1. Forests and management scenarios under bark beetle outbreak

Most of the bark beetle studies simulated stands dominated by Norway spruce (*Picea abies)*, with a limited representation of Scots pine, silver fir, and European beech. In all the studies *I. typographus* had Norway Spruce as the main host. In fact, this beetle species can also attack silver fir but with minor damage. Forests dominated by coniferous tree species, as opposed to mixed stands of coniferous and deciduous trees, with large tree diameter are particularly vulnerable to bark beetle infestations and this susceptibility is further exacerbated during drought years (Müller et al., 2022; Thiele et al., 2017). The rationale for the large diameter threshold for attack is that the bark of smaller trees is too thin to shelter adult beetles and provide sufficient nutrients for offspring development. The higher representation of studies from temperate forests compared to the boreal forests is likely related with the current higher incidence of bark beetle outbreaks in the former. This is likely explained by the evidence that the cooler climate in boreal forests is not favoring the population dynamics of thermophilic insects as well as climate in temperate regions where more successful beetle generations can be expected in a year. However, with the recent increase in windthrow events in northern Europe has contributed to the accumulation of large quantities of deadwood suitable for developing the infection of *Ips* (Sanginés de Cárcer et al., 2021). For bark beetle outbreak most of the simulations were conducted at the level of single trees and stands, with few exceptions conducted recently at the landscape level (Ďuračiová et al., 2020; Fustel et al., 2024; Romeiro et al., 2025; Seidl et al., 2009), and at the strategic temporal scale of one rotation period. This time window for simulations is congruent with the observation that bark beetle outbreak damages are observed only after one to two growing seasons after the attack.

As for windthrow, the management practice simulated most often was a reference scenario consisting of even-aged rotation forestry based on thinning followed either by shelterwood or clearcutting. Business-as-usual was frequently considered as the benchmark to evaluate production efficiency while accepting moderate risks of beetle outbreaks due to reliance on traditional harvesting schedules (e.g., Jönsson et al., 2015; Fustel et al., 2024). BAU was often associated with pre-commercial thinning as a way to improve tree health and lower bark beetle risk by reducing stand density and competition-induced stress. BAU was contrasted with other practices that can alter the risk of bark beetle outbreak, like SRL and ERL, which respectively reduce and increase the supply of old trees which are more susceptible to infestations (Fustel et al., 2024; Romeiro et al., 2025), promoting mixed forests (PMF), which can reduce the quota of vulnerable trees, and CCF, which can instead increase the susceptibility throughout the entire planning horizon by increasing the abundance of large Norway spruce trees in the forest (Jönsson et al, 2015; Seidl et al., 2008; Fustel et al., 2024). In general, Fustel et al. (2024) found that diversity-oriented forestry based on a combination of management strategies avoids local concentration of high risk of infestation spreading it at lower intensity across the landscape, resulting in reduced overall forest susceptibility to damage.

3.2.2. Management recommendations based on simulation of bark beetle outbreak

As bark beetle outbreaks take often place after trees have been killed or weakened by windthrow events and root rot infections, the DSSs forecasting their outbreaks also include models for simulating the risk of windthrow and root rot (c.f., Jönsson et al. 2015; Subramanian et al., 2016). These DSSs are mainly suitable for scientific assessment of various silvicultural recommendations. Consequently, the management recommendations to prevent the risk of bark beetle outbreak correspond to the methods used to reduce windthrow and root rot. These include increased stand tree density, avoiding intensive thinning, SRL, PMF and planting genetically improved Norway spruce seedlings as a mitigation measure (Subramanian et al., 2016; Thiele et al., 2017; Zimová et al., 2020; Nordkvist et al., 2023). Earlier research indicates that spruce stands will be increasingly susceptible to bark beetle attacks with extended rotation length (Nordkvist et al., 2023). Dobor et al. (2020) found that very high salvaging intensities (i.e., >95 % of disturbed trees detected and removed) would be required to prevent bark beetle risk. On the stand level the PMF strategy can make a difference in lowering forest susceptibility to bark beetle attacks.

3.2.3. *Management recommendations based on optimization of timber and bark beetle outbreak*

Fustel et al. (2024) optimized the boreal landscape to study the impact of management on forest vulnerability to bark beetle damage and potential trade-offs with biodiversity and timber production. They applied a first optimization model aiming to maximize harvest volume production, and a second optimization minimizing the spruce bark beetle susceptibility index (Nordkvist et al., 2023) subject to harvest volume demands above tree diameter size thresholds. In the optimization models, potential treatment schedules included a reference strategy, mimicking current management practices, and four alternative strategies to decrease spruce bark beetle damage: PMF, SRL with no thinnings, ERL and CCF. Two opposite strategies, i.e., SRL and ERL, were tested because they create contrasting forest structures associated with different risk profiles for bark beetle infestation. SRL by keeping stands young reduces the proportion of old/senescent trees preferred by bark beetles; ERL by increasing structural diversity can either increase or decrease vulnerability depending on the stand conditions. In addition, in a combined strategy, optimization models could choose treatment schedules out of all five individual management strategies.

Bark beetle risk can also be addressed at stand level when selecting the optimal rotation time (Romeiro et al., 2025). This method assumes no prior knowledge of infestation, making it suitable for addressing immediate risks. Bark beetle infestation risk shortened the optimal rotation time by 0–25 years, averaging 2–4 years. This reduction is greater than that caused by root rot, reflecting the faster mortality rates associated with bark beetle damage.

3.3. *Impact of forest management on root rot damage risk*

3.3.1. *Forests and management scenarios under root rot damage*

Root rot can impact almost all tree species depending on the infective agent. However, the root rot studies included in our review simulated almost exclusively growth of pure plantations of Norway spruce in boreal forests. This is because the simulation models mostly focus on Heterobasidion root rot on Norway spruce as it is the most common disturbance agent and the "easiest" to include in models. For example, in Finland 90 % of the root rot is *Heterobasidion*, and of that 90 % is *H. parviporum*, which only affects Norway spruce. But when in Sweden, for example, the percentages change and more of the root rot is caused by *H. annosum* which can again infect all tree species. Two studies have evaluated the effect of the spatial pattern of the admixture of spruce and pine on root rot development (Möykkynen and Pukkala, 2011; Ahtikoski et al., 2024), Möykkynen and Pukkala (2011) found the admixtures reduced root rot development dramatically, but Ahtikoski et al. (2024) found that this effect can vary within a latitudinal gradient. Root rot is caused by several different fungal agents causing decay in tree roots and stem and making them more prone to windthrow. This may lead also to increased exposure to bark beetle infestation (Wahlman et al., 2025). The simulations were conducted at the level of single trees or stands, and for one rotation period, which allows for root rot decadal development manifested during harvesting.

Most of the simulations were conducted under even-aged rotation forestry with variable timing in the commercial thinnings. Scenarios differed in the risk of infection, determined by initial number of infected stumps from the previous generation, spreading capacity from infected stumps (Möykkynen et al., 2000), probability of spore infection and spore density (Honkaniemi et al., 2014; 2017a), but also due to tree location compared to the extraction road and timing and intensity of thinning and clearcutting during the year (Möykkynen et al., 1998; Möykkynen and Pukkala, 2010).

3.3.2. *Management recommendations based on simulation of root rot damage*

The decision of which tree species to plant to reduce root rot damage has been studied using simulations. Möykkynen & Pukkala (2011) simulated the effect of the proportion of Norway spruce trees with root rot on the development of the stand. They noted that at the age of 20 years, root rot decreased strongly when Scots pine seedlings were planted around clear-felling stumps previously colonized by *Heterobasidion* (species complex). Möykkynen and Pukkala (2011) suggest that the main reason for the lower amount of root rot in mixed stands is that the average distance between Norway spruce trees is greater, which decreases the spread of *H. parviporum* from tree to tree. There are also fewer root contacts between Norway spruce trees in mixed forests.

Honkaniemi et al. (2014) combined the simulation of the spread of root rot to the MOTTI forest growth simulator showing that infected stumps from the previous tree generation have a substantial role on the prevalence of the infections. Honkaniemi et al. (2019) found that stump treatment with either chemical or biological control agents was financially viable in relatively healthy stands with high spore pressure for primary infection. However, the profitability decreased in stands with high decay levels and secondary infection pressure, indicating the need for targeted treatment strategies based on stand conditions.

Subramanian et al. (2016) combined random natural disturbance events to a process-based forest simulator (i.e., Heureka Standwise). The results highlighted the importance of reducing thinning intensity and rotation lengths to prevent root rot infections, along with windthrow damage and spruce bark beetle outbreaks.

In conclusion, these studies emphasize the significance of three essential tools to mitigate the negative consequences of root rot infections: targeted stump treatment, selection of alternative tree species and reduction in thinning and rotation length.

However, most of the available DSSs require information that forest owners do not usually have, and thus the usefulness of the DSSs for supporting decision making for a specific stand or estate is limited. For instance, the simulator of Honkaniemi et al. (2014) requires substantial input information of the current level of infection, e.g. number of infected stumps and the mean distance between stumps. The simulator developed by Subramanian et al. (2016) requires, among others, making assumptions on the input data to account for the uncertainty in the future climate scenarios, e.g. total monthly solar radiation, monthly minimum and maximum temperatures and rainfall. Due to the input demands, these approaches cannot be used to support decisions in a specific stand or estate but are useful for scientific analyses and silvicultural recommendations. These simulators are also suitable for analyzing the interactions of natural disturbances, e.g. that of wind throw risk and root rot risk (Honkaniemi, 2017a, b; 2018).

3.3.3. *Management recommendations based on optimization of timber and root rot risk*

The implementation of FNDMs in DSSs enabled optimization of the stand level rotation timing (Aza et al., 2021) using varying degrees of site productivity and rot infections. Aza et al. (2021) described the risk of root rot using probabilistic scenarios of rot. The scenarios included realizations of rot with a probability of rot observed in the Norwegian National Forest Inventory, and with models describing its spread within the infected tree (diameter and height of the rot). They maximized the soil expectation value at single stand level. Since the rot spread was in the analysis slower than tree growth, the optimal rotations were shortened by only 1–2 years if the owner had no prior information on the occurrence of the rot. This approach is applicable for harvest scheduling in standing forests, to account for the immediate risk with no additional information.

Aza et al. (2022a) further optimized economic outcomes by applying plantation of mixed species stands of susceptible (spruce) and non-susceptible species (pine) compared to pure stands of susceptible species. However, the change of species was more likely in the case of low site fertility. This study also highlighted that the spatial information of the infected trees was valuable, as it allowed planting spruce at location with no rot observations and corresponding low risk of being infected (Aza et al., 2022b). Ahtikoski et al. (2024) also optimized the planting of spruce based on the information of the location of the rot in the previous generation. This strategy can be seen as reactive, deciding what to do following observed rot in a clear-cut, but can be seen also as proactive as it reduces the risk of rot for the future generations of trees.

Möykkynen et al. (2000) implemented a DSS dealing with root rot to maximize the soil expectation value at the stand level. The forest owner was assumed to have information of the proportion of the infected trees at the time of planting, and a model was used to predict the spread of the rot within the stand based on this information. The optimization also included the possibility to utilize stump treatment before planting the new tree generation. This strategy can also be seen as reactive, i.e. reacting to the presence of the rot in current generation, to optimize the handling of the disturbance in the next generation.

Optimization can also be used to make recommendations for adaptive harvest decisions at the stand level. For instance, Möykkynen et al. (2000) recommended that if any stump infection by *H. annosum* occurred, one thinning resulted in a higher soil expectation value than two or no thinnings, also with the stump treatment. In areas with high risk of stump infection by *H. annosum*, the number of thinnings should be reduced and their timing delayed. Möykkynen and Pukkala (2009) further emphasized the importance of reducing thinning intensity. Moreover, incorporating Scots pine into stands reduced the occurrence of root rot in Norway spruce trees, particularly when facing logging injuries (Möykkynen & Pukkala 2010). Since the optimization in these papers starts after clear cutting, with known infection rate, this approach can be mainly utilized to produce silvicultural guidelines for proactive management but is rarely applicable for stand- or estate level decision support.

3.4. Impact of forest management and climate change on wildfire damage risk

3.4.1. Forests and management scenarios under wildfire risk

The sole European simulation study to analyze the damage of forest fire in boreal or temperate forests simulated the growth of Scots pine with admixed Norway spruce and birch (Næsset et al., 1997). They simulated the forest at stand level for a single rotation period (70 years) and applied an even-aged rotation with number of thinnings and length of rotation determined by optimization.

3.4.2. Management recommendations based on forest simulation under wildfire risk

One approach to decision support regarding wildfire was to simulate the occurrence and impact of fires as a function of the potential availability of fuel in the forests (e.g. Kloster et al., 2010). The fuel available within the forest must be dealt with to reduce the extent and intensity of forest fires. Therefore, the effects of fuel removal through prescribed burnings have been also simulated (e.g. Khabarov et al., 2016; Williams and Abatzoglou, 2016). In the fire risk management, the human component is important, as human ignition is an important cause of wildfires.

3.4.3. Management recommendations based on optimization of timber and wildfire risk

In Central and Northern European forests, examples of the implications derived from optimization studies related with wildfire risk are currently lacking, therefore we have referred in this paragraph to examples from the Canadian boreal forest. Even though Næsset et al. (1997) is an optimization study, the implications for forest management were not explicitly accounted for. The first published paper to quantify the optimal stand level rotation length under risk of wildfire was presented by Reed (1984). He maximized the land expectation value and showed that the higher the probability of the fire, the shorter the optimal rotation. In a case of fire, the 100-year optimal rotation with no risk and zero interest rate reduced to 49 years with 5 % fire probability and 5 % discount rate. The large effect compared to root rot and bark beetle is due to the assumption that none of the wood can be salvaged after the fire, and that the damage happens very fast even compared to the bark beetle damage.

To explore the impact of fire risk at a landscape level, Boychuk and Martell (1996) conducted a study to assess the impact of fire on a selection of timber production goals. In their case, shortening of the rotation was not the optimal solution, as being prepared for the fire risk required keeping up a larger storage of growing stock that would have been optimal without the landscape level goals.

Another approach to wildfires compares losses from risk-reduction actions to those due to the fire events. The minimum of the sum of these two losses is the optimal management cost (Martel & Boychuck, 1997). In a more recent study, Rijal et al. (2018) utilized cost-benefit analysis with a similar purpose. These approaches can be used to decide the optimal level of personnel and equipment maintenance to minimize the fire losses. As these studies were conducted in Canada, the viewpoint is that of a fire manager rather than of a forest owner, due to land-ownership structure issues.

3.5. Impact of forest management on snow and ice damage risk

3.5.1. Forests and management scenarios under snow and ice accumulation

The studies for snow damage and risk simulated growth of mixed coniferous and deciduous plantation forests. Most of the studies were carried out in the boreal forest and simulated the growth of Norway spruce with admixtures of Scots pine and birch. The unique example from temperate forests is from Canada, where a complex mixture of deciduous species was simulated (Tremblay et al., 2005). In only one case the joint impact of windthrow and snow damage was simulated (Díaz-Yáñez et al., 2019). The management practices simulated more often were even-aged rotation forestry, based on thinning followed by clearcutting, which was contrasted against a set-aside scenario (Päätalo, 2000).

3.5.2. Management recommendations based on simulation of snow and ice accumulation

Päätalo (2000) applied a snow accumulation model to investigate the susceptibility of managed stands to uprooting and breakage compared to unmanaged stands. They observed that managed stands were generally less susceptible to uprooting and breakage, except for unmanaged Norway spruce stands, which were less susceptible to uprooting. Scots pine was identified as the most susceptible species to uprooting and breakage, followed by Norway spruce. In contrast, birch was found to be less susceptible to these risks. The main factors influencing breakage risk were stem taper, with young stands having higher risks, while uprooting risk was higher in older/taller stands due to tree height being the main driving factor. Thinning was shown to reduce the risk of stem breakage and uprooting in Scots pine and birch stands in the long term, as well as the risk of stem breakage in Norway spruce stands. Kilpeläinen et al. (2010) also found that increasing stand volume increased risks associated with snow accumulation. Tremblay et al. (2005) instead focused on the impact of stand structure scenarios on forest recovery after ice damage. Although no active management was applied, they tested two scenarios - heterogeneously and uniformly distributed tree locations. The study found that recovery was faster in the heterogeneous scenario, indicating that stand structure plays a critical role in the regeneration and resilience of forests to ice disturbance. These simulations can be used to formulate general silvicultural guidelines for snow management.

3.5.3. Management recommendations based on optimization of timber and snow and ice risk

In general, the damages caused by snow and ice are a consequence of windthrow, therefore their models are an extension of the models developed for windthrow. However, different types of forests are at the highest risk for snow and wind damage. Young Scots pine stands are especially prone to snow damage while older Norway spruce stands are more prone to wind damage. Therefore, management recommendations for reducing the damage in terms of e.g. species selection and rotation length would be different for wind and snow. For instance, Díaz-Yáñez et al. (2019) explored the effects of accounting for the risk of snow and wind damage on optimal rotation length at the stand level. Also here, increasing discount rates lead to shorter rotations. Risk management resulted in lower growing stock volumes, particularly towards the end of the rotation. Their findings indicated that it was advantageous to remove economically valuable trees earlier and decrease stand density when managing under risk. However, the damage models used in this work were based on the damage observations in the Norwegian National Forest Inventory, which does not separate between wind and snow damage, so the two different damage types were also modelled together, as these two processes can act jointly in a damage event (c.f., Suvanto et al., 2021). For example, wind can more easily break trees with heavy snow load, or strong winds can either increase or prevent the accumulation of snow on trees by shedding the snow from the branches. Therefore, also the recommendations were the same for wind and snow. However, while these processes can be related to each other, Suvanto et al. (2019), 2021) show that snow damage and wind damage affect different types of forest stands and have also spatially different occurrence patterns. While wind damage risk increases with tree height, snow damage is more typical in smaller trees. In addition, snow damage can also occur with a minimal effect of wind (Hlásny et al., 2011) and wind disturbances often are not accompanied by snowfall. The challenge in considering wind and snow separately in national forest inventory data is in reliably identifying the cause of the damage in the field when field measurements are not targeting any specific damage event and stem breakages and uprooting can be related to either of the damage causes or their combined effects (Valinger and Fridman, 1999). For example, in southern Finland less common heavy snow events may be mistakenly classified as more common wind damage. The damage may have occurred already several years before the field measurement, making the correct identification of damage cause even harder. Yet, while this uncertainty needs to be acknowledged we conclude that, due to the differences in the two disturbance processes, it is beneficial to study damage caused by wind and by snow separately.

4. Discussion

Since 2005 the study of FNDMs and their implementation in DSSs increased dramatically. In Nordic countries, this is possibly explained by the increased timber utilization in recent years, that has almost reached the production frontier (c.f., Heinonen et al., 2017), and disturbances are seen as hampering forest productivity and carbon stocks (Lundmark et al., 2014), with limited opportunities to replace damaged stands. This increase in simulations embedding FNDMs is likely also due to the perception of the increased frequency and severity of the impacts of disturbances on temperate and boreal forests triggered by extreme events induced by climate change (cf., Chen et al., 2018; Subramanian et al., 2019; Whitman et al., 2019). Most of the studies were conducted in Nordic countries, and only few in temperate countries. This evidence can be related with a longer history in the development of DSSs in Nordic countries, which has brought forest managers to employ DSSs more for actual decisions (Kangas et al., 2015).

The increase in the number of studies is mostly due to the development of models to predict the effects of windthrow, and secondarily to the development of models for insect infestation and fungal disease. The most modelled disturbance was windthrow likely because this is the most significant and sudden disturbance agent for forests (Wohlgemuth et al., 2022b). In the boreal and temperate forests this disturbance is directly related with all the other disturbances, as proven by the interaction studies mostly including windthrow and another disturbance (Romeiro et al., 2022). The core suggestion is to develop forest management plans capable to reduce the impact of windthrow, and this will reduce the severity of other related disturbances. Wildfire and drought, on the other hand, have been much less simulated in Central and Northern European countries. Wildfire has currently only marginal effects in temperate and Nordic countries compared to southern Europe, and its occurrence is reduced by the milder climate and consequently by the more limited productivity (Migliavacca et al., 2013) and minimized with effective suppression (Aalto and Venäläinen, 2021). On the other hand, even though awareness has grown over the intensive tree dieback caused by drought in the north American boreal forest (e.g., in Canada, Hogg et al., 2008; Michaelian et al., 2011) and the connection between drought and insect outbreaks (McDowell et al., 2011; Forzieri et al., 2021), drought modeling remains detached by modeling of other disturbances in DSSs. In general, the studies including more than one disturbance were limited (12.5 %), due to the still limited conceptualization of their interactions and of the consequences for forest development (Romeiro et al., 2022).

The applicability of the modelling approaches needs to be considered in addition to the disturbance-specific patterns. The *categorization* of the specific characteristics of the DSSs and FNDMs largely determine the problem specific applicability, limitations, and the ability of the model to develop in the future (Fig. 3). Our review demonstrates that DSSs incorporating FNDMs have mostly relied on a *methodological approach* based on simulation to explore the impacts of disturbances rather than on optimization to improve management actions (Fig. 3). The *focus* has been on simulating windthrow, with bark beetles and root rot damage being moderately represented, and wildfire and drought being only marginally addressed (Fig. 3). Models representing disturbances are typically applied at the *spatial scale* of the stand or of the landscape and mainly at the *temporal scale* of strategic or tactical planning, with relatively few operational tools (Fig. 3). These distinctions shape the type of management recommendations they produce as well as their application.

Across the reviewed studies, episodic disturbances are included in optimization models in several ways, though the approaches remain limited. Windthrow is typically handled through predefined disturbance scenarios or risk indicators guiding rotation length or harvest timing, while bark beetle and root rot models adjust optimal rotations or species choice based on elevated damage likelihood during specific stand stages. Wildfire-related optimization remains rare and mainly focuses on shorter rotations under fixed disturbance probabilities. Overall, optimization studies remain economically oriented and represent uncertainty, disturbance timing, and interactions only partially, leaving the treatment of episodic events relatively underdeveloped.

Integrating disturbance models into decision support systems should enhance our understanding of how management can adapt and mitigate the negative impacts. From the perspective of *management strategies*, the distinction between *proactive* and *reactive* management strategies also highlights an important direction for future DSS development (Fig. 3). Proactive strategies such as adjusting rotation lengths, promoting species mixtures, or preventive thinning mitigate potential future forest vulnerability. Reactive strategies such as salvage logging or sanitary cutting can guide strategies for managing the negative outcomes. By improving DSSs to link predictions more directly to stand-specific recommendations would increase their relevance for operational decision-making and align outputs more closely with the needs of forest managers.

The most relevant *advances* which are still needed to efficiently model the complexity of disturbance are the FNDM integration into DSSs, improved modelling of windthrow and bark beetle outbreaks, and better modelling of disturbance interactions (Fig. 3). Yet, important *challenges* remain, including the still limited representation of multiple interacting disturbances, the mismatch between model scales and stand-level management needs, and the complexity of data and tools required

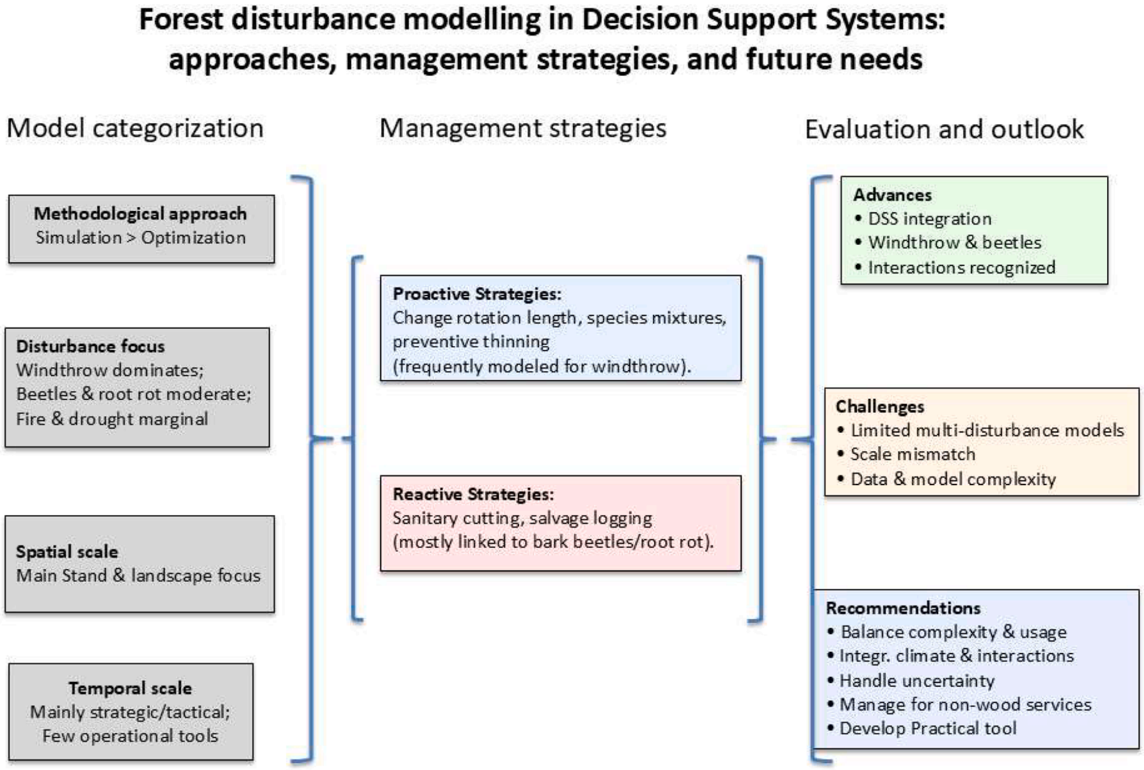

Fig. 3. Summary of forest disturbance modelling in DSSs: approaches, management strategies, and future needs.

that may limit their adoption by practitioners (Fig. 3). Building on these insights, we suggest *recommendations* for future development: to balance model complexity with usability; to better integrate climate change effects and interactions among disturbances; to incorporate uncertainty in a transparent and practical way; and to expand DSSs to include ecosystem services beyond timber, while developing tools that remain relevant for operational forest management (Fig. 3). By summarizing current approaches and highlighting these gaps, we provide a basis for guiding both methodological improvements and their application in practice.

The analysis of the simulated management scenarios across disturbances reveals that the vulnerability of forests is strongly influenced by species composition (Ahtikoski et al., 2024), stand structure (Tremblay et al., 2005), and management practices (Fustel et al., 2024). Conifer-dominated, even-aged plantations, particularly Norway spruce, are highly susceptible to windthrow, bark beetles, and root rot, whereas mixed-species stands exhibit greater resilience (Honkaniemi et al., 2018) respect to homogeneous coniferous stands (Thom, 2023). Snow and ice damage are more pronounced in younger, taller stands, with Scots pine being particularly vulnerable (Päätalo, 2000). While wildfire studies in boreal and temperate Europe remain limited (Næsset et al., 1997), fuel accumulation and stand density are critical risk factors (Kloster et al., 2010). These findings emphasize the need to consider species diversity, stand heterogeneity, and disturbance interactions when evaluating forest vulnerability to disturbances.

The management strategies applied in DSS studies can be generally classified as proactive, when forestry treatments are applied under immediate disturbance risk, or reactive, when treatments are applied after the impact of a natural disturbance was observed. The simulations studies included in our review consistently highlight proactive strategies as key to mitigating risks across disturbances. Proactive management includes measures from designing clear-cut areas to minimizing the windthrow risk at the edge of the forest (Ruotsalainen et al., 2022) or applying controlled burnings to reduce fire risk by removing forest fuel (Williams and Abatzoglou, 2016). On the other hand, for example, proactive management favors the creation of stands with mixed species (Sebald et al., 2021) to reduce the risk of bark beetle attack and the treatment of stumps with fungicides (Wang et al., 2015) to reduce the risk of root rot spreading. A common proactive strategy to deal with possible immediate risk of disturbance (e.g., windthrow, fire and bark beetle infestation) is to maximize the expected NPV of forest stands under the risk. This generally leads to shortened rotation period. This approach is particularly effective under high probability of damage (Reed, 1984; Potterf et al., 2022; Romeiro et al., 2025). Instead, for the disturbance from root rot, when the development of the damage is much slower than tree growth, reducing rotation is not very effective and other options should be considered (Aza et al., 2021). At larger scale decision making, stochastic optimization has been used to secure the required timber resources under the fire and wind risk (Boychuk and Martell, 1996; Eyvindson et al., 2024).

Reactive management strategies can be applied after the damage. For instance, salvage cuttings are used to remove any useful timber after windthrow and fire. Clear cutting the area around the dead trees can be applied in a sanitary cutting to prevent further spread of bark beetles' outbreaks. The selection of alternative tree species can prevent further spreading of root rot damage once its exact location is known (Aza et al., 2022a,b; Ahtikoski et al., 2024).

We classified the reviewed studies separating model-driven DSSs that employ only simulations and DSSs that also apply optimization. We excluded instead data-driven DSSs utilizing geographic information systems. Generally, maps of high-risk areas are the only readily useful means of decision support for forest owners. The maps are easy enough to utilize and can be used to locate areas where proactive strategies to tackle forest disturbances might be most useful (Rogan et al., 2006; Segura et al., 2014). However, maps do not provide any support for tasks such as harvest scheduling. A single map cannot be utilized for evaluating management strategies or policies, but if future maps were generated under different management strategies, they might be useful as a decision support tool.

Thus, the most useful approach to evaluate and compare forest management strategies could be to utilize a simulation based DSS. As including all natural disturbances simultaneously in a DSS is currently technically unfeasible, it is important to concentrate on the effects of the most important disturbances, whose impacts on forest dynamics can be predicted on the basis of standard inventory data. For example, in the boreal forest, the root rot, bark beetle and storms with current damage level reduce the land economic value when compared to a "No-damage" scenario. Obviously, their combined effect brings a larger reduction in economic value. Besides, in the future the infection rate of these risk factors may increase and then be more intense and expensive counter measures might be required (Subramanian et al., 2016). However, these DSS integrating simultaneously more disturbances may be too complicated to be used by managers and policy makers, as the requirements for input data and computational power are too high. The reliance on detailed input data, such as soil and infection levels, limits the applicability of simulations for specific stand-level decision-making. Nevertheless, these DSSs would mostly be useful for researchers making recommendations for the strategies and policies.

Optimization approaches reveal the trade-offs between economic objectives and disturbance risk management. While minimizing risks often reduces NPV, combining risk reduction with economic goals can yield balanced solutions (Potterf et al., 2024). For windthrow (Eyvindson et al., 2024) and root rot (e.g., Möykkynen and Pukkala, 2009), optimizing rotation lengths and thinning schedules reduces risks while maintaining profitability. In bark beetle (Fustel et al., 2024) and wildfire scenarios (Boychuk and Martell, 1996), optimization and landscape-level planning prove essential to address vulnerabilities related to stand placement and structure. For assessing the timing of harvests under alternative disturbance regimes, in general, optimization would be the obvious choice. The currently available DSSs mainly feature stand-level analysis for selection of optimal rotation but only a few of them expand the optimization to the whole forest landscape (e.g., Mazziotta et al., 2023). The optimal rotation analysis, on the other hand, is often based on just one goal, namely maximizing the land expectation value of the forests or the timber revenues. This is likely because the most urgent concern about disturbance impacts is related to the reduction of the forest economic value, but other ecosystem services are currently at risk in Europe due to climate and land use change, such as carbon storage, soil erosion control and outdoor recreation (Lecina-Diaz et al., 2024).

At the landscape level, most often used approaches minimize vulnerability or the risk, but do not consider the cost of this minimization compared to the prevented losses. Thus, instead of utilizing an indicator of vulnerability as an objective, the optimization could include a loss function, i.e. an approximation of the impact of the damage, to be fully useful (e.g. Martell and Boychuk, 1997). A promising approach for solving harvest scheduling problems is the landscape-level stochastic optimization, which provides possibilities for freely selecting the objectives, explicitly stating the risk preferences of the forest owner (Eyvindson et al., 2024). However, this optimization approach is currently underdeveloped, as tools to generate a feasible set of representative scenarios of natural disturbances and their impacts are missing. Such set of scenarios might also require two-directional feedback between the FNDMs and the DSSs: for example, the changes in the structure of the stand predicted by the DSS at the end of each simulation period might change the shape of the wind profile in the windthrow model, with implications for the wind loading of individual trees under different forest configurations (Hanewinkel et al., 2010). Moreover, the stochastic approaches are very computing-intensive, meaning that for instance the development of national-level sustainability strategies might rely on a simpler forest simulator than the ones that are currently in use, for instance DSSs embedding stand- or age-class tables.

5. Conclusion

In conclusion, our review underscores the critical role of forest management in mitigating disturbances while balancing other goals in forest planning. Proactive strategies, such as species diversification, rotation length adjustment, and targeted thinning, emerge as key measures to reduce risks across windthrow, bark beetle, root rot, and snow damage. However, the effectiveness of these measures depends on detailed stand-level information, which remains a challenge for widespread application. Optimization approaches demonstrate that while minimizing disturbance risks often reduces NPV, integrated planning can balance risk reduction with economic feasibility. At both stand and landscape scales, optimizing rotation lengths, thinning schedules and species selection is crucial for enhancing forest resilience. Landscape-level planning offers opportunities to address spatial vulnerabilities and improve risk management outcomes. Despite advancements, limitations remain in integrating multiple disturbances within DSSs, particularly due to input data requirements and computational complexity. Future efforts should focus on improving the feasibility of DSSs for forest managers and policy makers while advancing landscape-level stochastic optimization approaches to assess trade-offs under diverse disturbance regimes. This will enhance the capacity to develop adaptive and sustainable forest management strategies in the face of increasing disturbance risks in Europe due to climate change (Grünig et al., 2026).

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Appendix A. Supplementary data

The following is the Supplementary data to this article: See the end of the manuscript.

CRediT authorship contribution statement

Adriano Mazziotta: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Kyle Eyvindson:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Katharina Albrich:** Writing – review & editing, Writing – original draft, Data curation. **Juha Honkaniemi:** Writing – review & editing, Writing – original draft. **Joyce Machado Nunes Romeiro:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Susanne Suvanto:** Writing – review & editing, Writing – original draft. **Annika Kangas:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, 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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2026.111565.

Data availability

List of references for the review is shared in supplementary material.

References

Aalto, J.U.H.A., Venäläinen, A., 2021. Climate Change and Forest Management Affect Forest Fire Risk in Fennoscandia. Finnish Meteorological Institute, p. 3. Reports, 2021.

Ahtikoski, A., Honkaniemi, J., Holmström, E., Peltoniemi, M., 2024. Optimal species composition for stand establishment in root-rot infected forest areas. New For. 55, 1425–1438. https://link.springer.com/article/10.1007/s11056-024-10046-w.

Altman, J., Fibich, P., Trotsiuk, V., Altmanova, N., 2024. Global pattern of forest disturbances and its shift under climate change. Sci. Total Environ. 915, 170117. https://doi.org/10.1016/j.scitotenv.2024.170117.

Aza, A., Kallio, A.M.I., Pukkala, T., Hietala, A., Gobakken, T., Astrup, R., 2022a. Species selection in areas subjected to risk of root and butt rot: applying precision forestry in Norway. Silva Fenn. 56 (3), 10732. https://doi.org/10.14214/sf.10732.

Aza, A., Kangas, A., Gobakken, T., Kallio, A.M.I., 2021. Effect of root and butt rot uncertainty on optimal harvest schedules and expected incomes at the stand level. Ann. For. Sci. 78, 70. https://link.springer.com/article/10.1007/s13595-021-01072-1.

Aza, A., Kangas, A., Kallio, A.M.I., 2022b. Value of information on root and butt rot presence when choosing tree species for a previously spruce-dominated stand in Norway. Forests 13 (10), 1562. https://doi.org/10.3390/f13101562.

Blennow, K., Sallnäs, O., 2002. Risk perception among non-industrial private forest owners. Scand. J. For. Res. 17, 472–479. https://doi.org/10.1080/028275802320435487.

Blennow, K., Andersson, M., Bergh, J., Sallnäs, O., Olofsson, E., 2010a. Potential climate change impacts on the probability of wind damage in a south Swedish forest. Clim. Change 99, 261–278. https://link.springer.com/article/10.1007/s10584-009-9698-8.

Blennow, K., Andersson, M., Sallnäs, O., Olofsson, E., 2010. Climate change and the probability of wind damage in two Swedish forests. For. Ecol. Manag. 259 (4), 818–830. https://doi.org/10.1016/j.foreco.2009.07.004.

Boychuk, D., Martell, D.L., 1996. A multistage stochastic programming model for sustainable forest-level timber supply under risk of fire. For. Sci. 42 (1), 10–26. https://doi.org/10.1093/forestscience/42.1.10.

Chen, L., Huang, J.G., Dawson, A., Zhai, L., Stadt, K.J., Comeau, P.G., Whitehouse, C., 2018. Contributions of insects and droughts to growth decline of trembling aspen mixed boreal forest of western Canada. Glob. Change Biol. 24 (2), 655–667. https://doi.org/10.1111/gcb.13855.

Daniel, C.J., Ter-Mikaelian, M.T., Wotton, B.M., Rayfield, B., Fortin, M.J., 2017. Incorporating uncertainty into forest management planning: timber harvest, wildfire and climate change in the boreal forest. For. Ecol. Manag. 400, 542–554. https://doi.org/10.1016/j.foreco.2017.06.039.

de Pellegrin Llorente, I., Eyvindson, K., Mazziotta, A., Lämås, T., Eggers, J., Öhman, K., 2023. Perceptions of uncertainty in forest planning: contrasting forest professionals' perspectives with the latest research. Can. J. For. Res. 53 (6), 391–406. https://doi.org/10.1139/cjfr-2022-0193.

Díaz-Yáñez, O., Arias-Rodil, M., Mola-Yudego, B., González-Olabarria, J.R., Pukkala, T., 2019. Simulating the effects of wind and snow damage on the optimal management of Norwegian spruce forests. Forestry 92 (4), 406–416. https://doi.org/10.1093/forestry/cpz031.

Dobor, L., Hlásny, T., Rammer, W., Zimová, S., Barka, I., Seidl, R., 2020. Is salvage logging effectively dampening bark beetle outbreaks and preserving forest carbon stocks? J. Appl. Ecol. 57 (1), 67–76. https://doi.org/10.1111/1365-2664.13518.

Ďuračiová, R., Munko, M., Barka, I., Koren, M., Resnerová, K., Holusa, J., Jakus, R., 2020. A bark beetle infestation predictive model based on satellite data in the frame of decision support system TANABBO. iForest 13 (3). https://doi.org/10.3832/ifor3271-013.

Ellis, T.M., Bowman, D.M., Jain, P., Flannigan, M.D., Williamson, G.J., 2022. Global increase in wildfire risk due to climate-driven declines in fuel moisture. Glob. Change Biol. 28 (4), 1544–1559. https://doi.org/10.1111/gcb.16006.

Eyvindson, K., Kangas, A., 2018. Guidelines for risk management in forest planning—What is risk and when is risk management useful? Can. J. For. Res. 48 (4), 309–316. https://doi.org/10.1139/cjfr-2017-0251.

Eyvindson, K., Kangas, A., Nahorna, O., Hunault-Fontbonne, J., Potterf, M., 2024. Integrating wind disturbances into forest planning: a stochastic programming approach. Silva Fen 58 (4), 23044. https://doi.org/10.14214/sf.23044.

Forzieri, G., Girardello, M., Ceccherini, G., Spinoni, J., Feyen, L., Hartmann, H., Cescatti, A., 2021. Emergent vulnerability to climate-driven disturbances in European forests. Nat. Commun. 12 (1), 1081. https://www.nature.com/articles/s41467-021-21399-7.

Fustel, T.L.A., Öhman, K., Klapwijk, M., Nordkvist, M., Sängstuvall, L., Lämås, T., Eggers, J., 2024. Impact of management strategies on forest susceptibility to spruce bark beetle damage and potential trade-offs with timber production and biodiversity. For. Ecol. Manag. 563, 121964. https://doi.org/10.1016/j.foreco.2024.121964.

Grünig, M., Rammer, W., Senf, C., Albrich, K., André, F., Augustynczik, A.L., Seidl, R., 2026. Climate change will increase forest disturbances in Europe throughout the 21st century. Sci. 391 (6789), eadx6329.

Hahn, T., Eggers, J., Subramanian, N., Toraño Caicoya, A., Uhl, E., Snäll, T., 2021. Specified resilience value of alternative forest management adaptations to storms. Scand. J. For. Res. 36 (7-8), 585–597. https://doi.org/10.1080/02827581.2021.1988140.

Hanewinkel, M., Peltola, H., Soares, P., González-Olabarria, J.R., 2010. Recent approaches to model the risk of storm and fire. For. Syst. 19, 30–47. https://doi.org/10.5424/fs/201019S-9286.

Heinonen, T., Pukkala, T., Mehtätalo, L., Asikainen, A., Kangas, J., Peltola, H., 2017. Scenario analyses for the effects of harvesting intensity on development of forest resources, timber supply, carbon balance and biodiversity of Finnish forestry. For. Policy Econ. 80, 80–98. https://doi.org/10.1016/j.forpol.2017.03.011.

Hlásny, T., Křístek, Š., Holuša, J., Trombik, J., Urbaňcová, N., 2011. Snow disturbances in secondary Norway spruce forests in Central Europe: regression modeling and its implications for forest management. For. Ecol. Manag. 262 (12), 2151–2161. https://doi.org/10.1016/j.foreco.2011.08.005.

Hogg, E.H., Brandt, J.P., Michaelian, M., 2008. Impacts of a regional drought on the productivity, dieback, and biomass of western Canadian aspen forests. Can. J. For. Res. 38 (6), 1373–1384. https://doi.org/10.1139/X08-001.

Honkaniemi, J., Ahtikoski, A., Piri, T., 2019. Financial incentives to perform stump treatment against heterobasidion root rot in Norway spruce dominated forests, the case of Finland. For. Policy Econ. 105, 1–9. https://doi.org/10.1016/j.forpol.2019.05.015.

Honkaniemi, J., Lehtonen, M., Väisänen, H., Peltola, H., 2017a. Effects of wood decay by Heterobasidion annosum on the vulnerability of Norway spruce stands to wind damage: a mechanistic modelling approach. Can. J. For. Res. 47 (6), 777–787. https://doi.org/10.1139/cjfr-2016-0505.

Honkaniemi, J., Ojansuu, R., Kasanen, R., Heliövaara, K., 2018. Interaction of disturbance agents on Norway spruce: A mechanistic model of bark beetle dynamics integrated in simulation framework WINDROT. Ecol. Model. 388, 45–60. https://doi.org/10.1016/j.ecolmodel.2018.09.014.

Honkaniemi, J., Ojansuu, R., Piri, T., Kasanen, R., Lehtonen, M., Salminen, H., Mäkinen, H., 2014. Hmodel, a Heterobasidion annosum model for even-aged Norway spruce stands. Can. J. For. Res. 44 (7), 796–809. https://doi.org/10.1139/cjfr-2014-0011.

Honkaniemi, J., Piri, T., Lehtonen, M., Siipilehto, J., Heikkinen, J., Ojansuu, R., 2017b. Modelling the mechanisms behind the key epidemiological processes of the conifer pathogen Heterobasidion annosum. Fungal Ecol. 25, 29–40. https://doi.org/10.1016/j.funeco.2016.10.007.

Härtl, F., Hahn, A., Knoke, T., 2013. Risk-sensitive planning support for forest enterprises: the YAFO model. Comput.. Electron. Agric. 94, 58–70. https://doi.org/10.1016/j.compag.2013.03.004.

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

Kangas, A., Korhonen, K.T., Packalen, T., Vauhkonen, J., 2018. Sources and types of uncertainties in the information on forest-related ecosystem services. For. Ecol. Manag. 427, 7–16. https://doi.org/10.1016/j.foreco.2018.05.056.

Kangas, A., Kurttila, M., Hujala, T., Eyvindson, K., Kangas, J., 2015. Decision Support For Forest Management, 30. Springer.

Kellomäki, S., Väisänen, H., 1997. Modelling the dynamics of the forest ecosystem for climate change studies in the boreal conditions. Ecol. Modell. 97 (1-2), 121–140. https://doi.org/10.1016/S0304-3800(96)01940-5.

Khabarov, N., Krasovskii, A., Obersteiner, M., et al., 2016. Forest fires and adaptation options in Europe. Reg Environ. Change 16, 21–30. https://doi.org/10.1007/s10113-014-0621-0.

Kilpeläinen, A., Gregow, H., Strandman, H., Kellomäki, S., Venäläinen, A., Peltola, H., 2010. Impacts of climate change on the risk of snow-induced forest damage in Finland. Clim. Change 99, 193–209. https://link.springer.com/article/10.1007/s10584-009-9655-6.

Kloster, S., Mahowald, N.M., Randerson, J.T., Thornton, P.E., Hoffman, F.M., Levis, S., Lawrence, D.M., 2010. Fire dynamics during the 20th century simulated by the Community Land Model. Biogeosciences 7 (6), 1877–1902. https://doi.org/10.5194/bg-7-1877-2010.

Knoke, T., Gosling, E., Thom, D., Chreptun, C., Rammig, A., Seidl, R., 2021. Economic losses from natural disturbances in Norway spruce forests–A quantification using Monte-Carlo simulations. Ecol. Econ. 185, 107046. https://doi.org/10.1016/j.ecolecon.2021.107046.

Korosuo, A., Pilli, R., Abad Viñas, R., Blujdea, V.N., Colditz, R.R., Fiorese, G., Grassi, G., 2023. The role of forests in the EU climate policy: are we on the right track? Carbon Balance Manag. 18 (1), 1–14. https://doi.org/10.1186/s13021-023-00224-0.

Kulha, N., Heikkinen, J., Holder, J., Honkaniemi, J., Kuronen, M., Laapas, M., Peltoniemi, M., 2024. Landscape configuration and storm characteristics drive spatial patterns of wind disturbance in boreal forest landscapes. Landsc. Ecol. 39 (7), 119. https://link.springer.com/article/10.1007/s10980-024-01916-x.

Lausch, A., Heurich, M., Fahse, L., 2013. Spatio-temporal infestation patterns of Ips typographus (L.) in the Bavarian Forest National Park, Germany. Ecol. Indic. 31, 73–81. https://doi.org/10.1016/j.ecolind.2012.04.008.

Lecina-Diaz, J., Senf, C., Grünig, M., Seidl, R., 2024. Ecosystem services at risk from disturbance in Europe's forests. Glob. Change Biol. 30 (3), e17242. https://doi.org/10.1111/gcb.17242.

Lundholm, A., Black, K., Corrigan, E., Nieuwenhuis, M., 2020. Evaluating the impact of future global climate change and bioeconomy scenarios on ecosystem services using a strategic forest management decision support system. Front. Ecol. Evol. 8, 200. https://doi.org/10.3389/fevo.2020.00200.

Lundmark, T., Bergh, J., Hofer, P., Lundström, A., Nordin, A., Poudel, B.C., Werner, F., 2014. Potential roles of Swedish forestry in the context of climate change mitigation. Forests 5 (4), 557–578. https://doi.org/10.3390/f5040557.

Martell, D.L., Boychuk, D., 1997. Levels of fire protection for sustainable forestry in Ontario: a discussion paper. In: Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre Technical Report TR-43. Sault Ste. Marie, ON.

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., … Zhou, B., 2021. Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change, 2.

Mazziotta, A., Borges, P., Kangas, A., Halme, P., Eyvindson, K., 2023. Spatial trade-offs between ecological and economical sustainability in the boreal production forest. J. Environ. Manage. 330, 117144. https://doi.org/10.1016/j.jenvman.2022.117144.

McDowell, N.G., Beerling, D.J., Breshears, D.D., Fisher, R.A., Raffa, K.F., Stitt, M., 2011. The interdependence of mechanisms underlying climate-driven vegetation mortality. Trend. Ecol. Evol. 26 (10), 523–532. https://doi.org/10.1016/j.tree.2011.06.003.

Michaelian, M., Hogg, E.H., Hall, R.J., Arsenault, E., 2011. Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest. Glob. Change Biol. 17 (6), 2084–2094. https://doi.org/10.1111/j.1365-2486.2010.02357.x.

Migliavacca, M., Dosio, A., Camia, A., Hobourg, R., Houston-Durrant, T., Kaiser, J.W., Cescatti, A., 2013. Modeling biomass burning and related carbon emissions during the 21st century in Europe. J. Geophys. Res.-Biogeo. 118 (4), 1732–1747. https://doi.org/10.1002/2013JG002444.

Möykkynen, T., Miina, J., Pukkala, T., 2000. Optimizing the management of a Picea abies stand under risk of butt rot. For. Pathol. 30 (2), 65–76. https://doi.org/10.1046/j.1439-0329.2000.00187.x.

Möykkynen, T., Miina, J., Pukkala, T., von Weissenberg, K., 1998. Modelling the spread of butt rot in a Picea abies stand in Finland to evaluate the profitability of stump protection against heterobasidion annosum. For. Ecol. Manag. 106 (2-3), 247–257. https://doi.org/10.1016/S0378-1127(97)00317-4.

Möykkynen, T., Pukkala, T., 2009. Optimizing the management of a Norway spruce stand on a site infected by heterobasidion coll. Scand. J. For. Res. 24 (2), 149–159. https://doi.org/10.1080/02827580902870508.

Möykkynen, T., Pukkala, T., 2010. Optimizing the management of Norway spruce and scots pine mixtures on a site infected by heterobasidion coll. Scand. J. For. Res. 25 (2), 127–137. https://doi.org/10.1080/02827581003667322.

Möykkynen, T., Pukkala, T., 2011. Effect of planting Scots pine around Norway spruce stumps on the spread of heterobasidion coll. For. Pathol. 41 (3), 212–220. https://doi.org/10.1111/j.1439-0329.2010.00673.x.

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

Næsset, E., Gobakken, T., Hoen, H.F., 1997. Economic analysis of timber management practices promoting preservation of biological diversity. Scand. J. For. Res. 12 (3), 264–272. https://doi.org/10.1080/02827589709355409.

Nikinmaa, L., de Koning, J.H., Derks, J., Grabska-Szwagrzyk, E., Konczal, A.A., Lindner, M., Muys, B., 2024. The priorities in managing forest disturbances to enhance forest resilience: A comparison of a literature analysis and perceptions of forest professionals. For. Policy Econ. 158, 103119. https://doi.org/10.1016/j.forpol.2023.103119.

Nordkvist, M., Eggers, J., Fustel, T.L.A., Klapwijk, M.J., 2023. Development and implementation of a spruce bark beetle susceptibility index: A framework to compare bark beetle susceptibility on stand level. Tree. For. People 11, 100364. https://doi.org/10.1016/j.tfp.2023.100364.

Panferov, O., Sogachev, A., Ahrends, B., 2010. Changes of forest stands vulnerability to future wind damage resulting from different management methods. Open Geogr. J. 3 (1), 80–90. https://doi.org/10.2174/1874923201003010080.

Patacca, M., Lindner, M., Lucas-Borja, M.E., Cordonnier, T., Fidej, G., Gardiner, B., Schelhaas, M.J., 2023. Significant increase in natural disturbance impacts on European forests since 1950. Glob. Change Biol. 29 (5), 1359–1376. https://doi.org/10.1111/gcb.16531.

Peltola, H., Ikonen, V.P., Gregow, H., Strandman, H., Kilpeläinen, A., Venäläinen, A., Kellomäki, S., 2010. Impacts of climate change on timber production and regional risks of wind-induced damage to forests in Finland. For. Ecol. Manag. 260 (5), 833–845. https://doi.org/10.1016/j.foreco.2010.06.001.

Peng, C., 2000. Understanding the role of forest simulation models in sustainable forest management. EIA Rev. 20 (4), 481–501. https://doi.org/10.1016/S0195-9255(00)00036-0.

Potterf, M., Eyvindson, K., Blattert, C., Burgas, D., Burner, R., Stephan, J.G., Mönkkönen, M., 2022. Interpreting wind damage risk–how multifunctional forest management impacts standing timber at risk of wind felling. Eur. J. For. Res. 141 (2), 347–361. https://doi.org/10.1007/s10342-022-01442-y.

Potterf, M., Eyvindson, K., Blattert, C., Triviño, M., Burner, R.C., Burgas, D., Mönkkönen, M., 2024. Diversification of forest management can mitigate wind damage risk and maintain biodiversity. Eur. J. For. Res. 143 (2), 419–436. https://link.springer.com/article/10.1007/s10342-023-01625-1.

Power, D.J., 2002. Decision Support systems: Concepts and Resources For Managers, 13. Quorum Books, Westport, pp. 1–20. https://dssresources.com/dsstypes/.

Päätalo, M.L., 2000. Risk of snow damage in unmanaged and managed stands of Scots pine, Norway spruce and birch. Scand. J. For. Res. 15 (5), 530–541. https://doi.org/10.1080/028275800750173474.

Reed, WJ., 1984. The effects of the risk of fire on the optimal rotation of a forest. J. Environ. Econ. Manag. 11, 180–190. https://doi.org/10.1016/0095-0696(84)90014-7.

Repo, A., Albrich, K., Jantunen, A., Aalto, J., Lehtonen, I., Honkaniemi, J., 2024. Contrasting forest management strategies: impacts on biodiversity and ecosystem services under changing climate and disturbance regimes. J. Environ. Manag. 371, 123124. https://doi.org/10.1016/j.jenvman.2024.123124.

Riguelle, S., Hébert, J., Jourez, B., 2015. WIND-STORM: a decision support system for the strategic management of windthrow crises by the forest community. Forests 6 (10), 3412–3432. https://doi.org/10.3390/f6103412.

Rijal, B., Raulier, F., Martell, D.L., Gauthier, S., 2018. The economic impact of fire management on timber production in the boreal forest region of Quebec, Canada. Int. J. Wildland Fire 27 (12), 831–844. https://doi.org/10.1071/WF18025.

Rogan, J., Miller, J., Wulder, M.A., Franklin, S.E., 2006. Integrating GIS and remotely sensed data for mapping forest disturbance and change. Understanding Forest Disturbance and Spatial Pattern: Remote Sensing and GIS Approaches, pp. 133–172.

Romeiro, J.M.N., Eid, T., Antón-Fernández, C., Kangas, A., Trømborg, E., 2022. Natural disturbances risks in European Boreal and Temperate forests and their links to climate change–A review of modelling approaches. For. Ecol. Manag. 509, 120071. https://doi.org/10.1016/j.foreco.2022.120071.

Romeiro, J.M.N., Strîmbu, V.F., Eid, T., Kangas, A., 2025. Optimizing forest management in the face of bark beetle risk. Ecol. Model. 507, 111160. https://doi.org/10.1016/j.ecolmodel.2025.111160.

Ruotsalainen, R., Pukkala, T., Ikonen, V.P., Packalen, P., Peltola, H., 2022. Mitigating the risk of wind damage at the forest landscape level by using stand neighbourhood and terrain elevation information in forest planning. Forestry 95 (4), 515–528. https://doi.org/10.1093/forestry/cpac013.

Sanginés de Cárcer, P., Mederski, P.S., Magagnotti, N., Spinelli, R., Engler, B., Seidl, R., Schweier, J., 2021. The management response to wind disturbances in European forests. Curr. For. Rep. 7, 167–180. https://link.springer.com/article/10.1007/s40725-021-00144-9.

Schafellner, C., Möller, K., 2022. Insect defoliators. Disturbance Ecology. Springer International Publishing, Cham, pp. 239–269. https://doi.org/10.1007/978-3-030-94394-6_10.

Schelhaas, M.J., 2008. The wind stability of different silvicultural systems for Douglas-fir in the Netherlands: a model-based approach. Forestry 81 (3), 399–414. https://doi.org/10.1093/forestry/cpn020.

Schelhaas, M.J., Nabuurs, G.J., Schuck, A., 2003. Natural disturbances in the European forests in the 19th and 20th centuries. Glob. Change Biol. 9 (11), 1620–1633. https://doi.org/10.1046/j.1365-2486.2003.00684.x.

Sebald, J., Thrippleton, T., Rammer, W., Bugmann, H., Seidl, R., 2021. Mixing tree species at different spatial scales: the effect of alpha, beta and gamma diversity on disturbance impacts under climate change. J. Appl. Ecol. 58 (8), 1749–1763. https://doi.org/10.1111/1365-2664.13912.

Segura, M., Ray, D., Maroto, C., 2014. Decision support systems for forest management: A comparative analysis and assessment. Comput. Electron. Agric. 101, 55–67. https://doi.org/10.1016/j.compag.2013.12.005.

Seidl, R., Fernandes, P.M., Fonseca, T.F., Gillet, F., Jönsson, A.M., Merganičová, K., Mohren, F., 2011. Modelling natural disturbances in forest ecosystems: a review. Ecol. Model. 222 (4), 903–924. https://doi.org/10.1016/j.ecolmodel.2010.09.009.

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

Seidl, R., Schelhaas, M.J., Lindner, M., Lexer, M.J., 2009. Modelling bark beetle disturbances in a large scale forest scenario model to assess climate change impacts and evaluate adaptive management strategies. Reg. Environ. Change 9, 101–119. https://link.springer.com/article/10.1007/s10113-008-0068-2.

Sturtevant, B.R., Fortin, M.J., 2021. Understanding and modeling forest disturbance interactions at the landscape level. Front. Ecol. Evol. 9, 653647. https://doi.org/10.3389/fevo.2021.653647.

Subramanian, N., Bergh, J., Johansson, U., Nilsson, U., Sallnäs, O., 2016. Adaptation of forest management regimes in southern Sweden to increased risks associated with climate change. Forests 7 (1), 8. https://doi.org/10.3390/f7010008.

Subramanian, N., Nilsson, U., Mossberg, M., Bergh, J., 2019. Impacts of climate change, weather extremes and alternative strategies in managed forests. Ecoscience 26 (1), 53–70. https://doi.org/10.1080/11956860.2018.1557315.

Suvanto, S., Lehtonen, A., Nevalainen, S., Lehtonen, I., Viiri, H., Strandström, M., Peltoniemi, M., 2021. Mapping the probability of forest snow disturbances in Finland. Plos one 16 (7), e0254876. https://doi.org/10.1371/journal.pone.0254876.

Suvanto, S., Peltoniemi, M., Tuominen, S., Strandström, M., Lehtonen, A., 2019. High-resolution mapping of forest vulnerability to wind for disturbance-aware forestry. For. Ecol. Manag. 453, 117619. https://doi.org/10.1016/j.foreco.2019.117619.

Thiele, J.C., Nuske, R.S., Ahrends, B., Panferov, O., Albert, M., Staupendahl, K., Saborowski, J., 2017. Climate change impact assessment—A simulation experiment with Norway spruce for a forest district in Central Europe. Ecol. Model., 346, 30–47. https://doi.org/10.1016/j.ecolmodel.2016.11.013.

Thom, D., 2023. Natural disturbances as drivers of tipping points in forest ecosystems under climate change–implications for adaptive management. Forestry 96 (3), 305–315. https://doi.org/10.1093/forestry/cpad011.

Thürig, E., Palosuo, T., Bucher, J., Kaufmann, E., 2005. The impact of windthrow on carbon sequestration in Switzerland: a model-based assessment. For. Ecol. Manag. 210 (1-3), 337–350. https://doi.org/10.1016/j.foreco.2005.02.032.

Tognetti, R., 2017. Climate-smart forestry in mountain regions–COST action CA15226. Impact 2017 (3), 29–31. https://doi.org/10.21820/23987073.2017.3.29.

Tremblay, M., Messier, C., Marceau, D.J., 2005. Analysis of deciduous tree species dynamics after a severe ice storm using SORTIE model simulations. Ecol. Model. 187 (2-3), 297–313. https://doi.org/10.1016/j.ecolmodel.2005.01.038.

Triviño, M., Potterf, M., Tijerín, J., Ruiz-Benito, P., Burgas, D., Eyvindson, K., Duflot, R., 2023. Enhancing resilience of boreal forests through management under global change: a review. Curr. Landsc. Ecol. Rep. 8, 1–16. https://doi.org/10.1007/s40823-023-00073-0.

Valinger, E., Fridman, J., 1999. Models to assess the risk of snow and wind damage in pine, spruce, and birch forests in Sweden. Environ. Manag. 24, 209–217. https://link.springer.com/article/10.1007/s002679900227.

Wahlman, W., Kasanen, R., Lappalainen, L., Honkaniemi, J., 2025. Root rot increases the vulnerability of Norway spruce trees to ips typographus infestation. For. Ecol. Manag. 577, 122409. https://doi.org/10.1016/j.foreco.2024.122409.

Wang, L., Gunulf, A., Pukkala, T., Rönnberg, J., 2015. Simulated heterobasidion disease development in Picea abies stands following precommercial thinning and the economic justification for control measures. Scand. J. For. Res. 30 (2), 174–185. https://doi.org/10.1080/02827581.2014.961955.

Whitman, E., Parisien, M.A., Thompson, D.K., Flannigan, M.D., 2019. Short-interval wildfire and drought overwhelm boreal forest resilience. Sci. Rep. 9 (1), 18796. https://doi.org/10.1038/s41598-019-55036-7.

Williams, A.P., Abatzoglou, J.T., 2016. Recent advances and remaining uncertainties in resolving past and future climate effects on global fire activity. Curr. Clim. Change Rep. 2, 1–14. https://doi.org/10.1007/s40641-016-0031-0.

Wohlgemuth, T., Hanewinkel, M., Seidl, R., 2022b. Wind disturbances. Disturbance Ecology. Springer International Publishing, Cham, pp. 239–269. https://doi.org/10.1007/978-3-030-91841-4_9.

Wohlgemuth, T., Jentsch, A., Seidl, R., 2022a. Disturbance Ecology, Vol. 32. Springer Nature. https://doi.org/10.1007/978-3-030-91841-4.

Zeng, H., Garcia-Gonzalo, J., Peltola, H., Kellomäki, S., 2010. The effects of forest structure on the risk of wind damage at a landscape level in a boreal forest ecosystem. Ann. For. Sci. 67 (1), 111. https://doi.org/10.1051/forest/2009088.

Zeng, H., Peltola, H., Kellomäki, S., 2007a. Interactive clear-cut regime selection for risk management of wind damage using reference point approach. Ecol. Inform. 2 (2), 150–158. https://doi.org/10.1016/j.ecoinf.2007.05.001.

Zeng, H., Pukkala, T., Peltola, H., 2007b. The use of heuristic optimization in risk management of wind damage in forest planning. For. Ecol. Manag. 241 (1-3), 189–199. https://doi.org/10.1016/j.foreco.2007.01.020.

Zeng, H., Pukkala, T., Peltola, H., Kellomäki, S., 2007c. Application of ant colony optimization for the risk management of wind damage in forest planning. Silva Fenn. 41 (2), 315. https://doi.org/10.14214/sf.290.

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

Zubizarreta-Gerendiain, A., Pukkala, T., Peltola, H., 2017. Effects of wind damage on the optimal management of boreal forests under current and changing climatic conditions. Can. J. For. Res. 47 (2), 246–256. https://doi.org/10.1139/cjfr-2016-0250.