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To mix or not to mix—efficient adaptation to windthrow risk

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To mix or not to mix—efficient adaptation to windthrow risk

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Abstract

Disturbance to spruce forests from wind and bark beetles is projected to worsen. It has been suggested that mixed-species forests could provide a more disturbance-resilient option than spruce monocultures. We used dynamic optimization to study how profitable mixed forests are compared to pure spruce forests by examining two similar neighboring stands facing a windthrow risk. We found that under high current windthrow risk levels in northeastern Finland, Norway spruce (*Picea abies*)-only forests are more profitable than mixed forests consisting of spruce and silver birch (*Betula pendula*). However, if the windthrow risk to spruce trees increases by 35% compared to its current level, and the risk level of birch remains at its current level, mixed forests become more profitable. When carbon is priced at €50 per ton of CO_2, the additional income from carbon storage in mixed forests outweighs the economic advantage of spruce timber, making mixed forests more profitable—even if the risk to spruce increases by only 25%. Hence, mixed-species forests become increasingly profitable as carbon prices rise. Therefore, mixed-species forestry represents a cost-efficient strategy for adapting to increasing environmental risks and mitigating climate change.

1. Introduction

In Europe, forest disturbances due to natural events like storms, fires, and insect attacks have worsened over the last 100 years (Schelhaas *et al* 2003, Seidl *et al* 2011, Gregow *et al* 2017). On average, in the last two decades, about 80 million cubic meters of of damaged wood has been recorded each year, which is equivalent to about 16% of the mean annual harvest in Europe (Patacca *et al* 2022). Between 1950 and 2019, wind caused the most damage (accounting for 46% of the total timber volume damaged), mainly in Western, Central, and Northern Europe (Gardiner *et al* 2010), followed by fires (accounting for 24% of the total timber volume damaged), mainly in southern regions (Spain, Portugal, Italy, and Greece) (Pausas *et al* 2008), and bark beetles (accounting for 17% of the total volume disturbed), mainly in Central and Eastern Europe (especially Germany, Poland, Austria, and the Czech Republic) (Patacca *et al* 2022). Future projections suggest that forest disturbances in Europe are expected to increase significantly.

The susceptibility of forests to wind disturbance is shaped by a range of factors. Important influences include tree characteristics—such as species (with deep-rooted and flexible-stemmed species being generally more wind-resistant; Gardiner *et al* 2008), height, and root structure— and stand-level features such as density and age structure. For example, dense stands with tall, slender trees are typically more vulnerable than mixed-age or multi-layered forests (Nicoll *et al* 2006). Site conditions, including soil type and topography, and the type and structure of surrounding vegetation, also play significant roles (Schindler *et al* 2009). In addition, forest management practices such as thinning and rotation length can influence wind resistance (Beach *et al* 2009, Kim *et al* 2019, Cannon *et al* 2021), as can the structure of nearby forest stands (Mitchell 2013, Gardiner 2021). Forest edges adjacent to clearings are particularly exposed and more likely to suffer wind disturbance (Ruel 1995, Mitchell 1998, Lanquaye-Opoku and Mitchell 2005). Informed forest management decisions—such as species selection and harvest timing, as well as the choice of management regime (rotation forestry versus continuous cover forestry)—require models, as relationships among stand vulnerability, the environment, and management decisions are complex (Beach *et al* 2009, Potterf *et al* 2022).

Homogeneous spruce stands yield high short-term profits due to timber value (Knoke *et al* 2005, Brus *et al* 2011), but they are vulnerable to wind and pest disturbance (Overbeck and Schmidt 2012). High vulnerability to disturbance of spruce forests can lead to high financial losses over time, making species diversification a potentially more resilient strategy. Mixed forests are generally shown to be better at handling natural disturbances than forests with just one species (Hartley 2002, Knoke *et al* 2005, Nichols *et al* 2006, Griess and Knoke 2011). For a risk-aware forest owner/investor, mixed forests can also be more valuable financially (Knoke *et al* 2005).

The productivity of mixed-species stands depends heavily on species composition and factors such as stand age and density, which influence how species interact, particularly in terms of competition and complementarity (Kelty 1992). The strength of the relationship between species richness and forest productivity varies across climate zones, with more pronounced effects in resource-limited environments, such as arid or nutrient-poor regions (Zhang *et al* 2012). Climatic stressors, such as drought intensity, temperature extremes, and soil conditions, can further enhance the positive effects of diversity, especially when species differ in their resource-use strategies (Mina *et al* 2018). Generally, diverse communities are better able to buffer and adapt to challenging conditions (Staples *et al* 2019). While the ecological and recreational benefits of boreal mixed forests in Fennoscandia are well documented (Huuskonen *et al* 2021), their economic profitability remains less understood. Clarifying this relationship is important because ecological resilience can indirectly influence long-term forest income.

Mixed forests can also be an efficient climate change mitigation strategy, as they may store more carbon than single-species forests as disturbance risks are expected to become more significant in the future (Ruiz-Benito *et al* 2014, Mensah *et al* 2016, Blaško *et al* 2020, Assmuth *et al* 2021, Vuguls *et al* 2023, Warner *et al* 2023). This is also of interest for forest carbon markets and subsidies that can play a greater role in capturing carbon in the future (e.g., Gren and Aklilu 2016). Creating a market for carbon storage would encourage planting more diverse forests, especially when carbon prices are high and not all trees are valuable for timber (Assmuth *et al* 2021), which would reduce the risk of disturbance and carbon loss from the ecosystem. However, under the current climate, it has also been suggested that in the Boreal zone, Norway spruce monocultures may store more carbon than spruce –birch mixtures (Täll *et al* 2025), but it has also been found that the effectiveness of carbon capture is dependent on the species composition, stand structure, growth conditions, and selected management strategies (Thom and Keeton 2019, Yang *et al* 2024).

In this study, we used dynamic optimization to study the profitability of even-aged mixed-species forests. We focused on two adjacent even-aged and mixed-species stands composed of Norway spruce (*Picea abies*) and silver birch (*Betula pendula*) at a site in northeastern Finland, representing boreal forests in Fennoscandia. Earlier, Vuguls *et al* (2023) found that in conditions like Fennoscandian boreal forests, especially when managed for long-term sustainability, birch –spruce mixed forests can store more carbon in both biomass and harvested wood products compared to monocultures, making mixed stands particularly interesting systems to study. We focus on two forest owners who can reduce the wind disturbance vulnerability of their stands by choosing when to harvest and by planting different tree species while regenerating their stands after clear-cutting. Therefore, rather than having a constant optimal rotation, the optimal harvest age fluctuates over time as it is contingent upon the age of the neighboring stand (see e.g., Peterson and Cannon 2021). The study asks four main questions:

1. Are mixed forests or single-species forests more profitable when windthrow disturbance poses a risk?
2. How high are the economic costs of ignoring the risk?
3. What if the risk level of spruce trees increases compared to the current risk level, while the risk levels of other tree species remain the same?
4. Can carbon pricing make mixed forests more attractive than single-species ones?

2. Methods and data

We looked at the best way to manage two neighboring forest stands that are at risk of catastrophic wind disturbance. The disturbance is catastrophic in the sense that a disturbed stand requires immediate salvaging and regeneration. We looked at the two neighboring stands because the optimal time to cut down trees in any stand depends on the age and height of trees in neighboring areas, as the sudden exposure to wind increases the vulnerability of the trees (Meilby *et al* 2001, Heinonen *et al* 2009, Ruotsalainen *et al* 2023). Taller trees next to open areas are more likely to fall due to wind. Therefore, it is important to reduce the number of exposed edges in the forest (Zubizarreta-Gerendiain *et al* 2017). The forest stands were managed using an even-aged approach, meaning all trees in a stand were about the same age. Each stand had one planned thinning (removing some trees partway through growth), and the timing of the final harvest was optimized. Our goal was to find the plan that yields the highest total value from both timber and carbon income over time. We used dynamic optimization and maximized the expected net present value of timber and net income flows from carbon when the initial state was bare land. When the bare land value is considered, this value is known as the land expectation value (LEV). We studied how different mixes of tree species affect the LEV, assuming both forest stands have the same mix. We analyzed how varying the proportion of spruce in the forest mix influences the LEV, considering both the higher market value of spruce timber and its greater vulnerability to wind disturbance compared to birch. We compared two situations:

1. The 'optimal' case, where the forest owner considers the risk of wind disturbance, including the additional risk at the edges between the two stands, when deciding on the optimal adaptive clear-felling age.
2. The 'Faustmann' case, where the owner ignores the risk of wind disturbance, i.e., assumes it to be negligible (the probability of the windthrow event is zero), and uses the Faustmann formula (Faustmann 1849) to decide the optimal fixed clear-felling age.

2.1. The problem of the forest owner—a theoretical model

Our theoretical model followed Lintunen *et al* (2025). In this model, a forest owner manages two separate but adjacent one-hectare forest stands. In each period, t, for both stands, separate decisions are made about whether to make a final harvest, denoted as $\gamma_{it} \in \{0,1\}$, where 1 is a final harvest. The harvest value of the trees on the stand i at a period t, $h_i(a_{it})$, depends on the current age of the stand, a_{it}. After either a final harvest or natural wind disturbance, the stand is cleared, and a new cohort of trees is planted.

The age of a stand in the next period depends on the current age, a_{it}, harvest decision, γ_{it}, and wind disturbance realization, D_{it}:

$$a_{i,t+1} = a_i^+(a_{it},\gamma_{it}; D_{it}) := \gamma_{it} + (1 - \gamma_{it})[D_{it} + (1 - D_{it})(a_{it} + 1)], \tag{1}$$

where $D_{it} \in \{0,1\}$ indicates whether a wind disturbance happened, $D_t = 1$, or not, $D_t = 0$. In each year, the occurrence of disturbance is realized after the harvest decision, so the forest's age used in the disturbance probability model is the after-harvest age, $\tilde{a}_{it} := (1 - \gamma_{it})a_{it}$. For the stand i, the probability of a disturbance is expressed through a function:

$$P_{it} = P_i(\tilde{a}_{it}, \tilde{a}_{-it}), \tag{2}$$

where $-i$ denotes the neighboring stand.

The influence of the neighboring stand occurs through the border effect, the strength of which depends on the average tree height difference between the stands. The wind disturbance realizations are drawn separately for both stands. We assumed that the draws are uncorrelated. Lintunen *et al* (2025) studied the implications of the correlation on optimal clear-felling policy and found them to be minor. Therefore, we focused exclusively on the uncorrelated case.[1] The joint distribution is formulated based on the binary random variables associated with each stand, with the joint probability for the disturbances (D_1, D_2) represented as $P_{D_1D_2}$. In each time period, the probabilities can be expressed as follows: $P_{11} = P_1P_2$, $P_{01} = (1 - P_1)P_2$, $P_{10} = P_1(1 - P_2)$, and $P_{00} = (1 - P_1)(1 - P_2)$. P with two indices represents the joint distribution, whereas P with a single index denotes the disturbance probability for an individual stand.

The forest owner wants to get the highest possible net present value from the money earned over time from both forest stands. For each year, the revenues are derived from harvest revenues, $h_i(a_{it})$, in cases where the forest stand is harvested, from salvage revenues, $\sigma h_i(a_{it})$, when windthrow hits the stand, or, in the case of positive carbon pricing, $p_{CO2} > 0$, from carbon rent, provided the stand is not disturbed by harvest or wind. If the forest is hit by wind disturbance, its harvest value can be retrieved partially by salvage logging. We assumed that the salvage value of the disturbed forest was 70% of the undisturbed forest's value, i.e., $\sigma = 0.7$. The carbon rent is calculated as the rental value of the carbon stock of the stand (the carbon stored in tree biomass): $p_{CO2}\rho S(a_{it})$ (Sohngen and Mendelsohn 2003). Here, p_{CO2} is the carbon price, for which we tested different values, starting from 0 €/tCO$_2$ and increasing to 50 €/tCO$_2$, ρ is the annual discount rate, for which we used a numerical value of 3%, and $S(a_{it})$ is the amount of stored carbon (tCO$_2$/ha). The cost of regeneration (artificial planting and seeding), C (€/ha), must be paid whenever the stand is disturbed. We used a value of 1300 €/ha

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[1] The empirical model of wind disturbances (Suvanto *et al* 2019) does not include information on correlation. Hence, incorporating correlation into the disturbance model would require distorting of the empirical formulation. As the effects of correlation have been assessed as minor (Lintunen *et al* 2025), we conclude that including correlation would not provide added value.

for C. Thus, we expressed the net revenues for each year and the stand, r_{it}, as a function:

$$r_{it} = r_i(\gamma_{it}, a_{it}; D_{it}) := [h_i(a_{it}) - C]\gamma_{it} + \{[\sigma h_i(a_{it}) - C]D_{it} + p_{CO2}\rho S(a_{it})(1 - D_{it})\}(1 - \gamma_{it}). \quad (3)$$

That is, the full harvest value net of regeneration cost is obtained if harvested ($\gamma_{it} = 1$), and if not harvested, either the salvage value net of regeneration cost is obtained when wind disturbance occurs, or the carbon rent is obtained if the stand remains undisturbed.

Leaving out the time indices, the forest owner's problem can be written recursively:

$$V(a_1, a_2) = \max_{(\gamma_1,\gamma_2)\in\{0,1\}^2} \sum_{D_1,D_2\in\{0,1\}} P_{D_1D_2}[r_1 + r_2 + \delta V(a_1^+, a_2^+)], \quad (4)$$

The value function $V(a_1, a_2)$ represents the optimized joint expected value of the forest stands when the stand ages are a_1 and a_2. The superscripts with a plus sign denote the next period values (see equation (1)). The expected value is defined through the probabilities $P_{D_1D_2}$ corresponding to each disturbance contingency (D_1, D_2). Additionally, $\delta = (1 + \rho)^{-1}$ is the annual discount factor, determining the present value of next-period cash flows. We implemented a dynamic optimization procedure in MATLAB using Gauss-Seidel value function iteration to solve the dynamic program (equation (4)). The algorithm iteratively maximized the value function over a discrete state space, accounting for stochastic disturbances and salvage values. At each iteration, the value function was updated based on four possible harvest combinations between two forest stands. The process continued until the maximum change in the value function fell below a predefined convergence threshold.

In forest economics, an often-used value concept is the land expectation value (LEV), that is, the expected net present value (NPV) of cash flows when starting from bare land. When the neighboring stand affects the development of a stand, the LEV is not a single value but depends on the state of the neighboring stand—in our case, its age. The value function, equation (4), aggregates the values of both stands, and therefore it does not determine the individual LEVs. However, when the stands are equal and both are at the youngest age class, we can calculate their LEVs simply as $LEV = \delta V(1,1)/2 - C$. In the numerical application, we simulated the harvest policies (optimal and suboptimal Faustmann rule). As the natural disturbances are random, the realized NPVs of cash flows are also random. The simulations were started from bare land, and therefore, the mean of NPVs is an estimator for the LEV. Hence, from the simulations, we could assess the LEV and its confidence interval, as well as the standard deviation of the NPVs.

2.2. A numerical application

2.2.1. A mixed-species forest growth model

For the numerical calculations, the stand projections were simulated using a mixed-species forest growth model created by Pukkala *et al* (2009), with young stand development based on the MOTTI forest simulator (Salminen and Hynynen 2001, Hynynen *et al* 2002, Salminen *et al* 2005). The Pukkala *et al* (2009) model consists of an individual-tree 5-year diameter increment model that predicts the annual growth in diameter at breast height (DBH) for individual trees, a height model (a modification of the Hossfeld model [e.g., Björn and Kiviste 1997]) that estimates tree height based on DBH and site characteristics, and a survival model that predicts the probability of individual tree survival over time. The survival model consisted of two sub-models, one for spruce and one for spruce and pine, which were logistic models. Logistic formulations guarantee that the predicted probabilities of survival will be between zero and one. Since the measurement intervals of data used to calibrate these models were six years, the models predicted six-year survival, which must be considered when using the models. The application area of the Pukkala *et al* (2009) model covers all growing sites, all main tree species, and the whole of Finland. There is also an ingrowth model, but we suppressed it as we focused on even-aged management with artificial regeneration.

2.3. Forest stand simulation

MOTTI is a forest stand simulator developed in Finland, primarily used for simulating the growth and management of boreal forests, especially those with Scots pine, Norway spruce, and silver birch as dominant species. It simulates growth at the individual tree level, allowing for detailed stand dynamics incorporating tree diameter, height, and crown dimensions. Its empirical growth functions are based on long-term forest inventory data from Finland. We used MOTTI to generate data that reflects conditions in northeastern Finland. Given that MOTTI simulations commence at the age of 25 and our optimization model initiates from the first year, we employed quadratic extrapolation to characterize the forest growth during the initial years. We employed modified Akima cubic Hermite interpolation (Akima 1970). The generated MOTTI data were used to describe the growth of the forest up until the first thinning, which happens at year 40, because MOTTI provided a realistic initial state of the forest stand. From there on, we used Pukkala *et al* (2009) to describe the

Table 1. Average timber prices (2019–2021) (Luke 2025).

	Spruce sawn log	Birch sawn log	Spruce pulpwood	Birch pulpwood
Clear-cut (€/m^3)	62.7	46.0	21.9	19.1
First thinning (€/m^3)	43.4	35.0	13.2	12.8

growth of the forest until the stand was 200 years old. Thus, we had a simulated description of the forest growth for 200 years, setting the upper limit for clear-cutting ages.

2.4. The harvest value of the stand

By using the model by Pukkala *et al* (2009) for simulating the forest growth, we assessed the volumes of harvestable pulpwood and sawn logs for each of the modeled size classes at any given time. Initially, the potential sawn and pulpwood sections of the stems were calculated using the species-specific stem taper functions from Laasasenaho (1982), considering the minimum diameters specific to each species and, for pulpwood, the minimum log length. In the second phase, an empirical model for the quality reduction of potential sawn logs (in terms of dimensions) was utilized (Mehtätalo 2002). The proportion of the potential sawn log volume considered unsuitable for sawn log applications was incorporated into the potential pulpwood volume. The resultant volumes of pulpwood and sawn logs were multiplied by the average stumpage prices specific to species and assortments (table 1). We ignored the price risks and cost fluctuations in this study.

2.5. Annually sequestered carbon dioxide

We utilized the models developed by Lehtonen *et al* (2004) to model the relationships between the dry weight of biomass components and stem volume, which was calculated for each tree at diameter at breast height by using equations from Laasasenaho (1982), whereas the biomass of each component of a tree was estimated from diameter at breast height using Swedish equations (Marklund 1988). These models provide the dry weight of the biomass of the stand based on the total volume of the stand. The models are tailored for various tree species. We converted the biomass carbon to CO_2 by multiplying it by 3.67 to estimate the amount of annually sequestered carbon dioxide.

2.6. The probability of windthrow disturbance

To estimate the risk of wind disturbance, we used the model from Suvanto *et al* (2019). The model calculates the probability of windthrow disturbance based on tree species, the average height of the trees, whether the stand is next to an open edge indicated by differences in adjacent stand heights (i.e., the border effect), the type of soil, wind speed, and how much disturbance has happened nearby, i.e., 'disturbance density.' We set the wind speed (i.e., the 10-year return level of maximum wind speed) to 24 m s^{-1}, which is in the high end of Finnish conditions. In addition, we assumed a relatively high-risk area with a high disturbance density. As Suvanto *et al* (2019) do not classify severities of the disturbances, but we focused on severe events, we scaled the overall probability downwards by 25% to reduce the number of events closer to one event per century. Truly catastrophic, landscape-scale windthrow events (comparable to natural disasters that wipe out vast forest areas) is estimated to occur once every several decades to once a century in Finland, depending on the growth environment (Valta *et al* 2019). The site can still be seen as a high-risk site in current conditions in Finland.

We slightly altered the functioning of the border effect from the paper by Suvanto *et al* (2019) in the following way. We changed the binary on/off effect to a linearly decreasing one. In Suvanto *et al*'s (2019) model, the border effect is activated when the weighted average height of either or both stands falls below 5 meters. This is logical, because trees that have been developed in sheltered environments and are subsequently exposed to wind are particularly vulnerable to damage (Lohmander and Helles 1987, Peltola *et al* 1999, Suvanto *et al* 2019). Nevertheless, as the trees mature, they also adapt to the prevailing wind conditions. Consequently, it is logical to conclude that the border effect diminishes as the neighboring trees grow. In addition, by using a linearly decreasing relation, we avoided sudden jumps that can be problematic in optimization. We used the average tree height of the stands for spruce and birch as an input to the risk probability model by Suvanto *et al* (2019) to obtain the windthrow disturbance risk probability for both tree species. Then we calculated an overall risk for the whole stand by averaging the risks for each species, based on how many trees of each type are present in the stand.

2.7. The windthrow disturbance risks of spruce and birch

The model by Suvanto *et al* (2019) shows that the risk for a birch is about half of that for a spruce (figure 1(a)). This means that when wind risk is considered, spruce-dominated forests might not be the most profitable

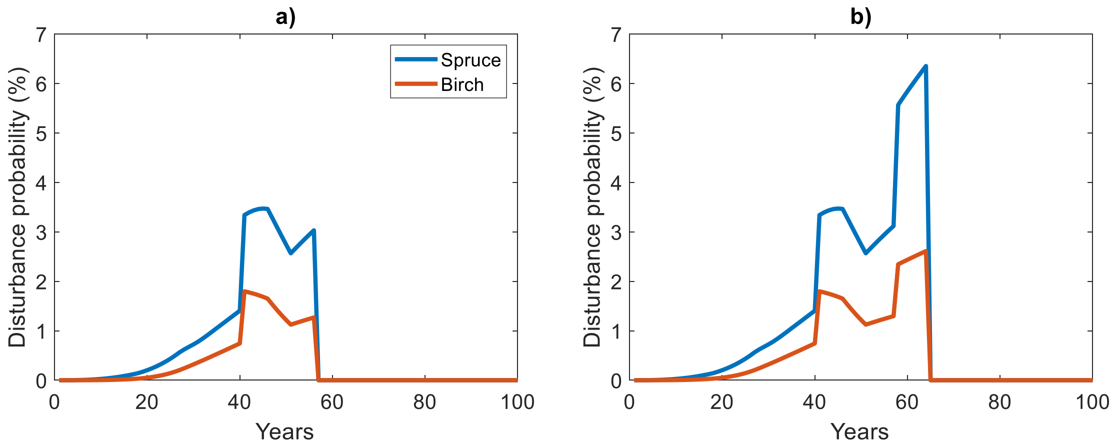

Figure 1. The evolution of the windthrow disturbance probabilities over time (the stand age) for spruce and birch as determined by the model from Suvanto *et al* (2019) in the case where the neighboring stands are clear-cut in the same year (panel a), and the same situation with the exception that the neighboring stand is clear-cut at the age of 58 and the stand in the figure is clear-cut at the age of 65 (panel b).

choice. Figure 1 also shows how the windthrow disturbance risk increases in time as the average height of the stand increases. Note that the disturbance probability increases notably at the time of thinning (year 40). After that, the influence of thinning on the disturbance probability gradually dies in 10 years, after which the disturbance probability increases because the trees get taller. After the clear-cut at age 58, the probability decreases to 0. (Note that the subsequent rotation is not simulated.) In the example shown in figure 1(a), the neighboring stands are identical, i.e., the clear-cut year is the same, and therefore the border effect is not active. Figure 1(b) demonstrates the active border effect. Here, the stand that is shown in the figure is clear-cut at the age of 65 (corresponding to the optimal Faustmann rotation for the pure spruce stand), whereas the neighboring stand is clear-cut at the age of 48. At this point, the disturbance probability jumps up notably. From there on, the probability continues to increase even further as the trees get taller.

2.8. The effect of carbon prices

We looked at how carbon prices affect the profits of mixed forests compared to forests with only spruce, especially when the risk of wind disturbance to spruce exceeds the baseline risk. As trees grow taller and older, they become more likely to be damaged by wind. Because older and taller trees are more susceptible to windthrow, policies that promote longer rotations for carbon storage inadvertently increase the exposure of forests to wind disturbance, thereby raising the overall risk. The value of storing carbon is based on the ‘social cost of carbon’ (SCC)—a common way to measure the damage caused by one ton of CO_2 emissions (Rennert *et al* 2022). We tested carbon prices ranging from 0€ to 50€ per ton of CO_2 and checked whether carbon pricing or wind disturbance risk has a bigger impact on forest profits.

2.9. Simulations

Following Moeller *et al* (2024), we simulated different mixtures of spruce and birch trees:

- 100% spruce (pure spruce stand)
- 75% spruce. 25% birch (slightly mixed stand)
- 50% spruce, 50% birch (mixed stand)
- 25% spruce, 75% birch (slightly mixed stand)
- 0% spruce, 100% birch (pure birch stand)

First, we used dynamic optimization to find the optimal year for a final harvest for each species mix and for the ‘optimal’ and the ‘Faustmann’ case (as defined earlier). Thus, the optimization runs gave us the optimal decisions for each case, i.e., those that maximized the LEV. Then, we ran Monte Carlo simulations to see how wind disturbance might affect the value of the forest over time. In these simulations, wind disturbance happens randomly based on known risk patterns defined by Suvanto *et al* (2019). Thus, the simulations gave us the realizations in a stochastic setting which correspond to the optimal decisions based on maximizing the LEV. Therefore, as in reality, in each individual simulation, the simulated LEV can be lower or higher than the LEV

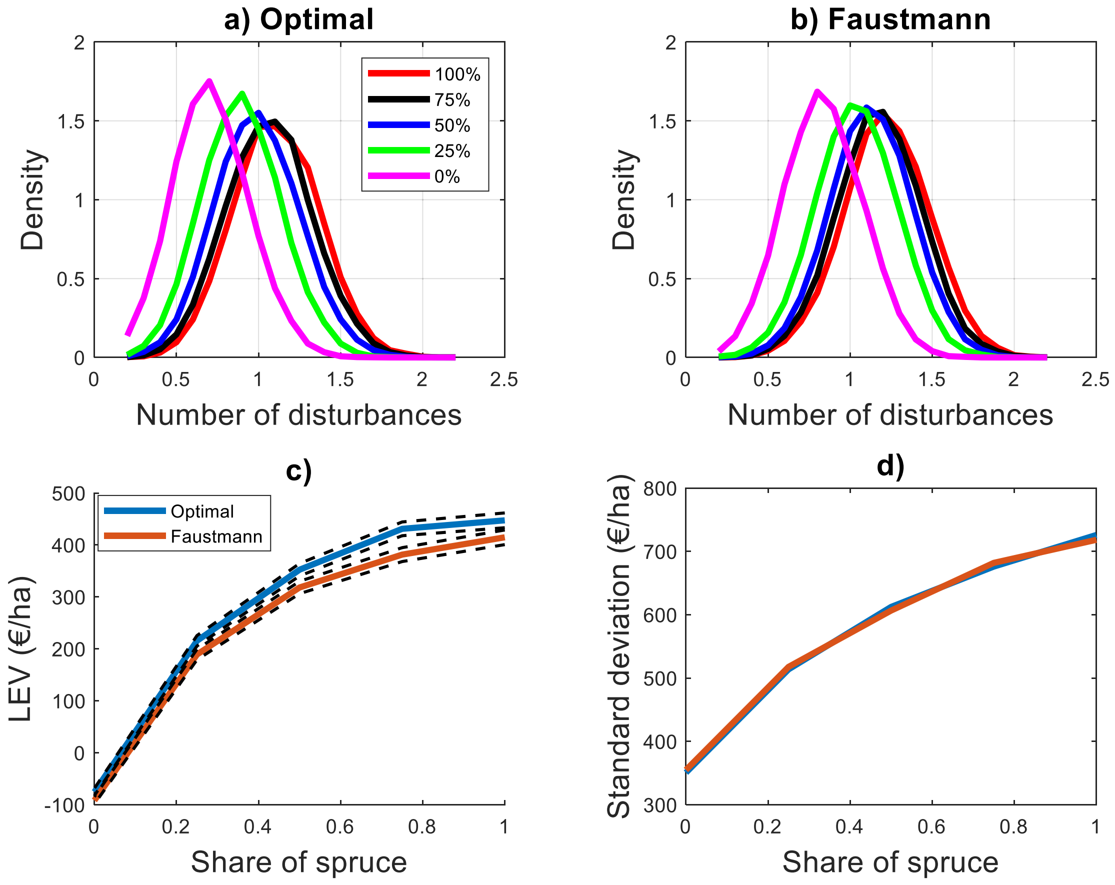

Figure 2. Distributions for the number of disturbances over 100 years for different species mixes (percentages indicate the proportion of spruce in the stand: 100% spruce [a pure spruce stand], 75% spruce and 25% birch [a slightly mixed stand], 50% spruce and 50% birch [a mixed stand], 25% spruce and 75% birch [a slightly mixed stand], 0% spruce and 100% birch [a pure birch stand]) and for the 'optimal' (a) and the 'Faustmann' (b) cases. Land expectation values (LEVs) for the 'optimal' and the 'Faustmann' cases for different species compositions under the baseline risk level and the associated error bars (dashed lines) (c). Standard deviations of the NPVs of cash flows, starting from bare land, for different proportions of spruce (d).

obtained in the corresponding optimization run. However, with a large enough number of simulations (10,000), the average simulated LEV was very close to the LEV obtained by optimization. Nevertheless, the simulated LEV is lower than that in the 'Faustmann' case because the risk was ignored in deciding about the optimal clear-cut year. By running the simulations over a 1,000-year horizon, we captured a wide range of possible disturbance scenarios. This allowed us to estimate not only the average economic return for each forest mixture but also the variability of outcomes, which is critical for assessing financial risk.

3. Results

3.1. Mixed versus monoculture stand—baseline case with low disturbance risk

Based on the Monte Carlo simulations and using the basic level of wind risk, a pure spruce forest was hit by about 1.1 disturbances every 100 years with the 'optimal' harvest policy, in which the forest owner takes wind disturbance risk into account, and about 1.2 disturbances with the fixed 'Faustmann' rotation, in which the owner ignores the risk of wind disturbance (see figures 2(a) and (b)). Thus, as the risk-ignorant 'Faustmann' rotations are longer than in the risk-aware 'optimal' case, the number of realized windthrow disturbances was about 10% higher. When introducing spruce –birch mixtures and optimizing harvest policies in the 'optimal' and the 'Faustmann' cases, the number of disturbances decreased. For example, in a forest with 75% spruce and 25% birch, the number of disturbances dropped by 3.6% in the 'optimal' case and 3.3% in the 'Faustmann' case, and in a forest with 25% spruce and 75% birch, the number of disturbances dropped by 20% in the 'optimal' case and 15% in the 'Faustmann' case (see figures 2(a) and (b)).

Although mixing spruce and birch reduced the frequency of wind disturbance, the higher market value of spruce timber outweighed the benefits of reduced risk. As a result, forests consisting of only spruce remained more profitable under high current risk conditions (figure 2(c)). In the 'Faustmann' case, profits were lower because wind disturbance risk was ignored, and the forest owner did not adjust harvest timing to mitigate

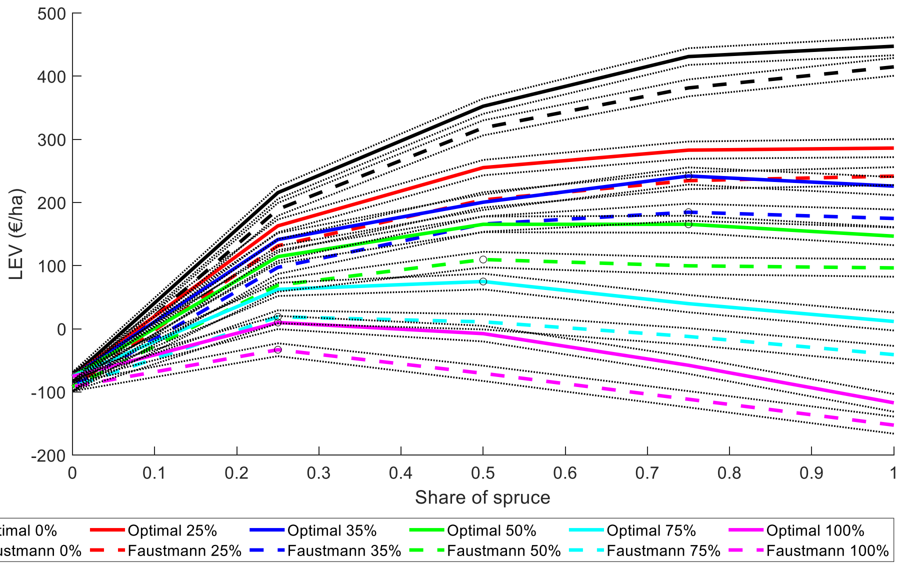

Figure 3. Land expectation values for the 'optimal' case (solid lines) and for the 'Faustmann' case (dashed lines) for different species compositions (with spruce share on the horizontal axis) and for different risk increase levels for spruce disturbances (percentages: 0% implies the baseline risk probability for spruce, 100% implies doubling the disturbance probability for spruce). The risk level of birch remains at its current level in all cases. Dotted lines denote the 95% confidence intervals.

potential losses. This led to more frequent and severe disturbance, reducing the overall bare land value, LEV. In the 'Optimal' case, where the risk is considered, the LEV was 26€ higher than in the 'Faustmann' case, when spruce made up 25% of the forest. For pure spruce forests (consisting of 100% spruce trees), the difference was even greater—33€ more in the 'optimal' case compared to that in the 'Faustmann' case. This shows that ignoring wind risk led to a bigger economic cost in spruce-only forests than in mixed forests. However, the gain in bare land value is relatively modest, as the disturbance events tend to occur late in the rotation, they are relatively infrequent, and shortening rotation implies lost revenue if disturbance does not occur. Finally, the net present value (NPV) of net cash flows was less uncertain in mixed forests compared to spruce monocultures (see figure 2(d)). It is also notable that the variation in the NPVs (shown here as standard deviation) arising from the stochastic windthrow disturbances is very high in comparison to its mean, i.e., the LEV (figure 2(c)). Hence, risk-averse forest owners could be inclined to prefer mixed-species stands.

3.2. Mixed versus monoculture stand—higher risk levels for spruce

Climate change may make spruce trees more vulnerable to wind damage than birch trees (Boulanger and Arseneault 2004). Figure 3 shows the effect of increasing wind damage risk to spruce while the risk level for birch remained at its current level while the risk level for birch remained at its current level. Mixing spruce and birch became the better option once the risk to spruce went up by about 35% compared to the current level. However, with a 50–50 mix, the profit was already clearly lower than that of a pure spruce stand. However, if the wind risk for spruce increased by 50%, then even a 50–50 mix became more profitable than a spruce-only forest (see figure 3). As the risk to spruce continued to rise, forests with more birch became even more profitable. These results were consistent across both the 'optimal' and 'Faustmann' cases.

3.3. Mixed versus monoculture stand—carbon price

The land expectation value (LEV) went up as the carbon price increased, independently of the tree species mixture or the wind disturbance risk level, in both the 'optimal' and the 'Faustmann' cases (figure 4). As far as the mixed versus monoculture question was considered, the result remained the same: when the risk to spruce trees was at a current level, the LEV increased as the amount of spruce in the forest increased. In this case, forests made up entirely of spruce were the most valuable—at low carbon prices (figure 4). However, when the carbon price reached 50 €/tCO$_2$ and the risk to spruce trees increased by just 25%, in the 'optimal' scenario, a forest with 75% spruce and 25% birch became more valuable than a spruce-only forest (figure 4(f)). This was a smaller increase in risk compared to when there were no carbon subsidies, where a 35% increase was sufficient to make mixed forests more profitable (see figure 3). In the 'Faustmann' scenario, even a lower carbon price of 40 €/tCO$_2$ was sufficient for the same 75–25 spruce-birch mix to become more valuable than a spruce-only forest —again, when spruce risk increased by 25% (see figure 4(e)).

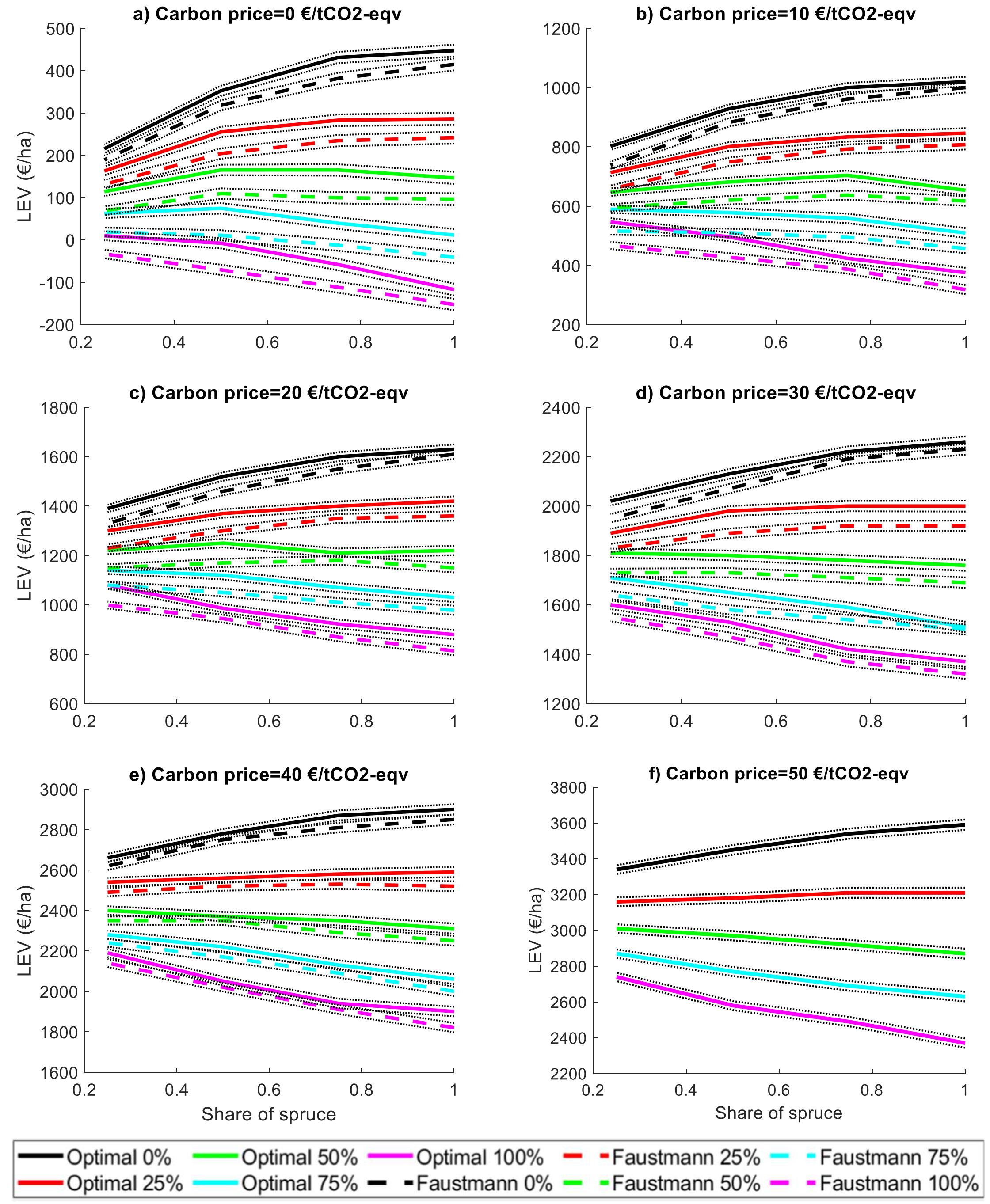

Figure 4. Land expectation values for the 'optimal' and the 'Faustmann' cases across varying spruce proportions in mixtures for different carbon prices under different disturbance risk levels for spruce. Dotted lines denote the 95% confidence intervals. Note that this figure does not show the cases where the stand is a pure birch stand because in those cases the optimal rotation exceeds 200 years, which is the maximum for which we have determined the value function. For the same reason, in panel (f), 'Faustmann' cases are excluded.

High carbon prices encouraged longer forest rotations in both the 'optimal' and the 'Faustmann' cases (figures 5(a), (c)), which increased the risk of windthrow disturbances (figures 5(b), (d)). Higher carbon prices increased the value of the carbon stored in standing trees. As a result, delaying harvest allowed more carbon to accumulate, which generated greater income from carbon credits and made longer rotations more financially attractive. This was because the additional money earned from storing more carbon outweighed the added risk from postponing the clear-cuts. In a pure spruce stand, when the carbon price increased from 0 €/tCO_2 to 50 €/tCO_2, the optimal rotation increased by 28% in the 'optimal' case and by 35% in the 'Faustmann' case (figures 5(a), (c)). The rotation- lengthening effect of the carbon price was milder in the 'optimal' case because the increased windthrow risk was considered in that case, which was a direct result of the taller trees. In the Faustmann model, this risk was ignored, leading to a sharper increase in rotation lengths as the carbon price

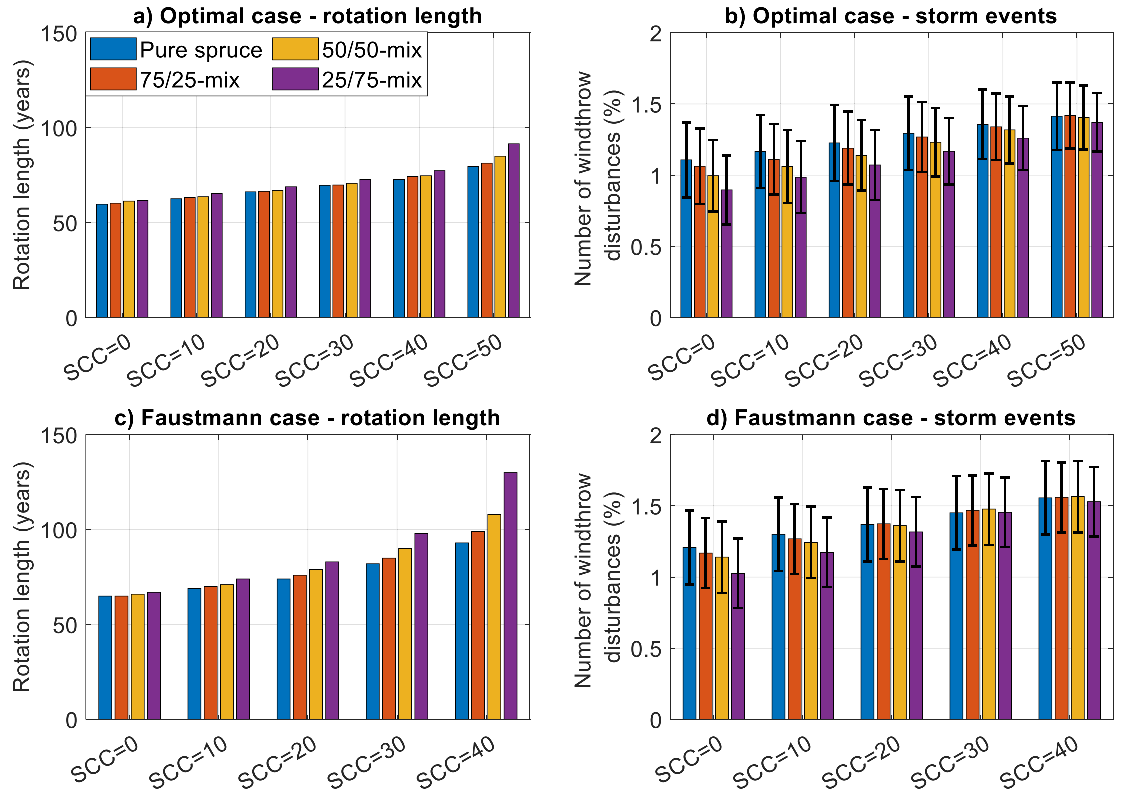

Figure 5. Optimal rotation lengths for different species mixtures (100% spruce, 75% spruce / 25% birch, 50% spruce / 50% birch, 25% spruce / 75% birch) in the 'optimal' and 'Faustmann' cases ((a) and (c), respectively); average number of windthrow disturbances in 100 years for different species mixtures in the 'optimal' and in the 'Faustmann' cases ((b) and (d), respectively). Here, SCC refers to the social cost of carbon, i.e., the carbon price.

rose. As a result of the longer rotations, in the 'optimal' case the average number of windthrow disturbances increased by 34% when the carbon price rose from 0 to 50 €/tCO$_2$, whereas the corresponding increase was 46% in the 'Faustmann' case (figures 5(b), (d)). Thus, high carbon prices greatly increased the windthrow disturbance risks, especially when those were ignored in deciding on the optimal rotation lengths.

However, using a mix of tree species shortened rotation periods. This was because birch trees had a lower probability of windthrow disturbance than spruce (see figure 1), so mixing them made the forest more resilient. In mixed forests, the optimal time to harvest was slightly later than in spruce-only forests (figures 5(a), (c)). The optimal rotation length increased with higher proportions of birch in the stand. In addition, the rotation-lengthening effect of species mixing was stronger for the higher carbon prices and greater in the 'Faustmann' case than in the 'optimal' case. This was because, although adding birch to the stand reduced the risk, increasing the length of the rotations was still associated with higher windthrow disturbance risk, and therefore, in the 'optimal' case, the rotations in mixed stands were only slightly longer than in the pure spruce stand. As a result of mixing the species in the stand, the number of windthrow disturbances decreased in the 'optimal' case for the carbon prices that were below 50 €/tCO$_2$ (figure 5(b)). Note, however, that even at this high carbon price, the number of windthrow disturbances was less in the 25% spruce/75% birch stand than in the pure spruce stand. In the 'Faustmann' case, the situation was less clear because longer rotations and mixing the species had opposite influences on the risk probability (figure 5(d)).

Figure 6 shows the optimal share of spruce for different carbon prices and the risk levels for spruce, while the risk level of birch remains at its current level. When the carbon price was 0 €/tCO$_2$, the risk level of spruce had to increase by 50% making it optimal to include 25% birch in the stand in both the 'optimal' and the 'Faustmann' cases. When the risk level of spruce increased by 75%, the optimal share of spruce in the stand was only 50% in the 'optimal' case and 25% in the 'Faustmann' case. The situation remained rather similar for the carbon price of 10 €/tCO$_2$. However, when the carbon price rose to 20 €/tCO$_2$ and the risk for spruce increased by 50%, it became optimal to devote only 50% of the stand to spruce trees, regardless of whether risk was considered in the rotation decision-making. And when the carbon price was 30 €/tCO$_2$ and the risk for spruce increased by 50%, it became optimal to devote only 25% of the stand to spruce trees in both cases. When the carbon price was 40 €/tCO$_2$, the risk of spruce had to increase by 25% making it optimal to include birch in the

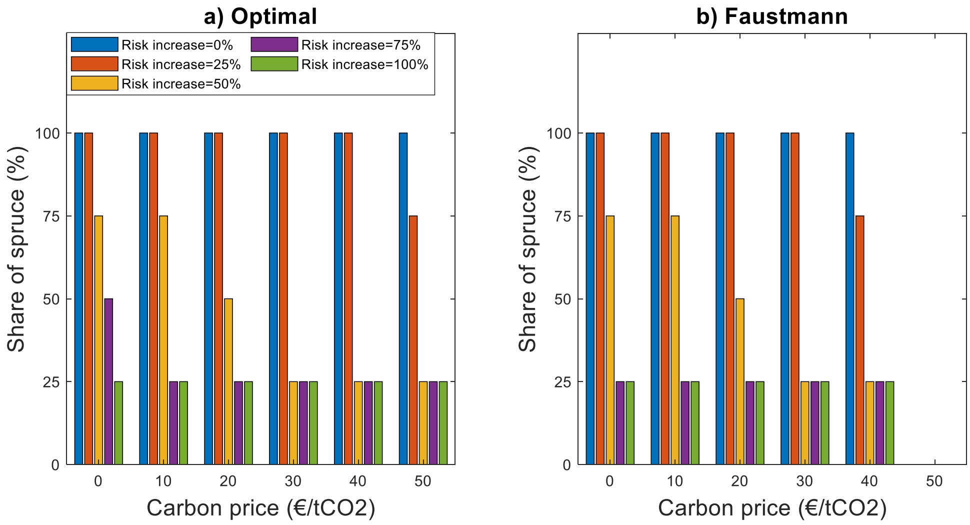

Figure 6. Optimal share of spruce for different carbon prices and spruce risk levels in 'optimal' (a) and 'Faustmann' (b) harvest policies. With a carbon price of 50 €/tCO_2-eqv, the Faustmann rotation exceeded 200 years and could not be evaluated.

stand (25%), in the 'Faustmann' case. For the same to happen in the 'optimal' case, the carbon price had to be 50 €/tCO_2.

4. Discussion

We looked at how profitable it is to manage forests with both spruce and birch trees in a situation where the influence of the nearby forest areas on the risk of windthrow disturbance is considered. In our study, when the windthrow risk was moderate, forests with only spruce trees were more profitable than mixed forests. But if the risk to spruce trees increased—as expected due to climate change—then mixing spruce and birch became more profitable. If forest owners were paid enough for the carbon stored in trees (in our case, 50 €/tCO_2), then mixed forests were the best choice even when wind risk was moderate. For owners who did not consider wind disturbance risks, a carbon price of 40 €/tCO_2 was enough to make mixed forests more profitable than pure spruce.

Our results showed that mixed forests do better when the risk of disturbance is high. This supports earlier findings by Willis *et al* (2019), who found that while pine-only forests had the highest economic value, mixed forests experienced lower economic losses during insect outbreaks. As climate change increases the risks to forests, mixing tree species may become a smarter and more economical choice. If wind disturbance risk was not considered when making forest management decisions (the 'Faustmann' case), the land value (LEV) was naturally lower than when the risk was considered (the 'optimal' case). The more at risk spruce trees were to wind, the bigger the gap between the two cases. This makes sense—if you ignore the risk, you miss the chance to manage it, and that becomes more costly as the risk increases. Also, the more birch trees there were in the forest mix, the less impact the rising spruce risk had on the land value. This was because birch was less affected by wind, so adding more birch helped reduce the overall risk. Thus, adding more birch reduced disturbance risk, especially when the forest owner took wind disturbance risk into account. So, owners who considered risk could benefit more from mixing tree species. These results are in line with Bourke *et al* (2023), who found that spruce monocultures are economically vulnerable under storm risk and that mixed stands, including species like European beech (similar in resilience to birch), showed better economic performance under wind risk scenarios.

Our findings also agree with other studies showing that mixed forests are effective at storing carbon (Chen *et al* 2023, Warner *et al* 2023, Moeller *et al* 2024). According to our results, as the risk of wind damage to spruce increased and carbon prices rose, the economic advantage of mixed forests became more pronounced. This is because birch, being less vulnerable to wind and still capable of storing carbon, contributed to both risk reduction and carbon income, making mixed stands more resilient and financially attractive. As a result, both higher carbon prices and higher spruce risk led to a lower share of spruce in the optimal forest mix. Even when wind risk remained constant, higher carbon prices increased the value of carbon storage. Since birch contributes to carbon storage while being less vulnerable to wind damage, reducing the share of spruce improves the overall economic return. Our results suggest that when wind disturbance risk was not actively managed, carbon pricing further increased the attractiveness of mixed forests. This happened because, in the 'Faustmann' case, trees were left to grow longer under each carbon price level compared to the 'optimal' case. These longer growing periods increased the chance of wind disturbance, which made mixing tree species a more useful way to reduce that risk. However, this effect was not very strong. These findings are in line with those of Assmuth *et al* (2021), who found that carbon pricing influences forest composition and management strategies. While their study showed an increase in spruce share with carbon pricing, they also emphasized that mixed stands with more species diversity reduce the marginal cost of carbon storage and enhance resilience. In addition, Vuguls *et al* (2023), who analyzed birch-spruce mixed stands, found that managed mixed forests contributed more to climate change mitigation than unmanaged ones. Their study considered both biomass and harvested wood products, showing that birch plays a significant role in carbon storage and product longevity, supporting our finding about birch contributing to carbon income and resilience.

Our results suggest that efforts to reduce climate change through carbon pricing (mitigation) also encourage forest owners to adopt practices that reduce vulnerability to climate-related disturbances (adaptation) by moving from monoculture to mixed-species forests. Thus, planting mixed-species forests not only enhances carbon storage but also improves resilience to wind disturbance, demonstrating how mitigation and adaptation strategies can reinforce each other. Policies like carbon pricing not only help reduce emissions but also encourage forest owners to prepare for future risks. These conclusions are in line with Hashida and Lewis (2019), who provided empirical evidence that carbon pricing and climate change pressures influence forest owners to adapt their management practices, including shifting species composition; the authors highlighted how carbon pricing not only incentivizes carbon sequestration but also indirectly promotes adaptation by encouraging species diversification. In addition, Ontl *et al* (2019) suggested that managing for carbon under changing climatic conditions requires integrating adaptation strategies, such as increasing species diversity and structural complexity, which also reduce vulnerability to disturbances. The results suggest that the risk of disturbances, like storms or pests, affects how profitable mixed forests are when carbon capture subsidies are involved. These results also suggest that climate programs can help forests adapt to climate change, not just reduce emissions (Ravindranath 2007). These findings suggest that forest policy can simultaneously support climate mitigation and adaptation. By incentivizing carbon storage through pricing mechanisms, policymakers can also promote forest compositions that are more resilient to disturbances. This dual benefit positions the forest sector as a key player in addressing both the causes and consequences of climate change. Therefore, our study adds a new view to earlier research. It suggests that carbon subsidy programs—like those in California and New Zealand (Carver *et al* 2022)—can make mixed-species forests more profitable. Our findings also support earlier studies showing that carbon pricing can make up for the risks of keeping forests uncut for longer (Daigneault *et al* 2010, Ekholm 2020). Also, according to our results, high carbon prices encourage planting a mix of tree species. Finally, our findings point to the conclusion that there can be synergies between adaptation and mitigation, supporting the previous literature stating that it is smart to prepare for more frequent disturbances, since they can seriously reduce the amount of carbon forests can store (Kurz *et al* 2008).

A useful next step in the study could be to include the economic value of biodiversity in the model in the form of financial payments, i.e., subsidies on increased biodiversity (measured, e.g., with the help of some sort of biodiversity index, such as the Shannon Diversity Index [DeJong 1975]). This could improve the profitability of mixed stands relative to monocultures. For example, replacing spruce-only forests with a mix of spruce and birch is expected to support more diverse plant and animal life (Carnus *et al* 2006, Brockerhoff *et al* 2008, Felton *et al* 2010, Wang *et al* 2019). It could also help to include the value people get from using forests for recreation, like hiking or enjoying nature. This added benefit could make mixed forests appear even more favorable from an economic point of view (Mattsson and Li 1994, Bostedt and Mattsson 1995). Like biodiversity values, recreational values are challenging to define. However, there are studies that aim to define the recreational value of a forest with willingness-to-pay methods (e.g., Riccioli *et al* 2019), with contingent valuation methods (e.g., Khalili Ardali *et al* 2024), and with meta-analysis (Rosenberger *et al* 2017). Another helpful addition would be to consider damage from pests and the impacts of tree species mixtures on these damage probabilities. Broadleaf trees, like birch, can help protect spruce trees from pests (Jactel and Brockerhoff 2007, Jactel *et al* 2009). So, including this in the model might show that mixed forests are not only more diverse but also more resistant, which could make them more profitable in the long run. Finally, we note that there is no model for the decomposition of dead trees in our modelling setup, and therefore we do not keep track of naturally dead trees, and the trees that have been damaged by windthrow are salvage logged. Leaving dead trees in place enhances carbon storage, supports biodiversity by providing habitat and stabilizing microclimate, and should be considered carefully in forest management that balances ecological benefits with economic interests (Radu 2006, Russell *et al* 2015, Wijas *et al* 2024, Bhardwaj *et al* 2025). Thus, extending the modelling setup with dead trees would be a model improvement worth examining.

While the risks of planting only spruce trees are well known, the economic benefits of using a mix of tree species in boreal forests has been less clear. This study showed that combining spruce and birch can be more profitable—especially when different species react differently to disturbance risks. As the value of capturing carbon increases with stronger climate goals, mixed forests will become an even smarter investment. This approach supports both climate mitigation (reducing emissions) and adaptation (preparing for climate impacts), demonstrating that they can work together rather than compete. To move forward, more research and pilot projects are needed to test and showcase these benefits (Parry *et al* 2001, Ravindranath 2007, Laukkonen *et al* 2009). This will help develop practical climate solutions that move beyond traditional approaches and support both forest health and economic resilience (Tol 2005, Xu *et al* 2019, Sharif 2020, Colelli *et al* 2023).

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Data availability statement

No new data were created or analysed in this study.

Author contributions

Matti Hyyrynen formulated the research question and design, performed all coding, calculations, and analyses, produced the results, and was primarily responsible for revising the manuscript. Jussi Lintunen contributed to the formulation of the research question and design, was mainly responsible for the theoretical framework, and participated in writing and revising the manuscript. Mikko Peltoniemi contributed to the formulation of the research question and design, and participated in writing and revising the manuscript.

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