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# Optimizing forest management in the face of bark beetle risk

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ABSTRACT

The rising impact of the spruce bark beetle (*Ips typographus* L.) on Europe's forests is becoming a major concern, with climate change intensifying the problem. This situation has sparked discussion across Europe about adopting new, adaptive forest management strategies to mitigate the economic impacts on the forestry sector. Despite this, some regions have yet to fully embrace long-term strategies against bark beetle outbreaks from a climate change perspective. In our study, we examined the effects of integrating bark beetle risk into forest management strategies, considering both current and future climate change scenarios. Our findings indicate that reducing rotation length of low density stands with a high proportion of Norway Spruce situated in more productive sites yields substantial economic advantages. Particularly, regions with a history of bark beetle outbreaks, like Vestfold in Norway, stand to gain significantly from early harvesting. The economic gain from harvesting earlier in this region is projected to increase nearly tenfold over the next 50 years under climate change scenarios. Additionally, we recommend considering the use of mixed tree species within forests as another adaptation strategy, to enhance forest resilience against bark beetle infestations and other natural disturbances.

## 1. Introduction

The impact of the European spruce bark beetle (*Ips typographus* L.) on forests has been a growing concern in Europe. The beetle primarily targets Norway spruce (*Picea abies* (L.) Karst), a dominant tree species in Southern Scandinavia and Central Europe (Schelhaas et al., 2018) that covers roughly 25% of Europe's total forest stock (Hlásny et al., 2021a). Under normal conditions, *I. typographus* reproduces in weakened or freshly killed trees, causing minimal changes to overall forest structure or species composition. However, once beetle populations surpass a critical threshold—often following abiotic stressors that reduce host-tree defenses—they can coordinate mass attacks on healthy spruce (Hlásny et al., 2019). Such outbreaks dramatically reshape forest dynamics by triggering widespread tree mortality, depleting local carbon stocks, and altering habitat structure.

The frequency and severity of bark beetle outbreaks have intensified in recent years, a trend closely linked to climate change. Rising temperatures accelerate beetle development, allowing multiple generations per year and increasing the likelihood of large-scale infestations (Jönsson et al., 2009; Marini et al., 2017). Additionally, prolonged drought events weaken Norway spruce defenses, making trees more susceptible to bark beetle attacks (Kausrud et al., 2012; Netherer et al., 2015). The extreme drought of 2018, one of the most severe in recent history (Buras et al., 2020), was followed by a series of devastating bark beetle outbreaks across Central Europe and Southern Scandinavia: In 2019, the Czech Republic recorded 20.7 million $m^3$ of spruce timber infested by bark beetles (Fernandez-Carrillo et al., 2020), while Germany reported 43.3 million $m^3$ of insect-damaged timber in 2020—primarily caused by bark beetles (Statistisches Bundesamt, 2021). Similarly, between 2018 and 2020, Southern Sweden lost approximately 17 million $m^3$ of spruce to *I. typographus* (Müller et al., 2022; Schroeder and Fritscher, 2020).

Looking ahead, the risk of further outbreaks continues to grow as climate conditions become increasingly unpredictable. Each year brings new record-breaking temperatures, and in 2024, Europe experienced its second warmest June on record, tying with 2022 (Copernicus Climate Change Service/ECMWF, 2024). Although Scandinavia currently experiences lower bark beetle pressure than Central Europe, climate change projections for the region suggest rising temperatures and drier summers in some areas (Belyazid and Zanchi, 2019; M N Romeiro et al., 2022). As

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a result, there is growing discussion across Europe about the need to develop adaptive forest management strategies to mitigate the long-term ecological impacts and economic losses from future outbreaks (Hlásny et al., 2017).

While climate acts as a key trigger, the susceptibility of forests to bark beetles is equally shaped by their structure and management. Older stands with high spruce volumes are particularly vulnerable (Hlásny et al., 2021a; Müller et al., 2022; Zimová et al., 2020). Therefore, among various strategies, the use of mixed species, both within and between forest stands, instead of Norway spruce monocultures, has emerged as a promising tool to improve ecological resilience (Kozhoridze et al., 2024; Sebald et al., 2021). Additionally, replacing Norway spruce trees with Scots pine trees when regenerating could be a viable option for locations with low to medium productivity, and low precipitation rates. Apart from that, the use of shorter rotation length to decrease bark beetle risk has been recommended in Central Europe (Dobor, Hlásny, and Zimová, 2020; Zimová et al., 2020), and has been used in Sweden since the storm Gudrun in 2005 (Subramanian et al., 2016). However, some regions have seen relatively few efforts and considerations related to long-term measures against bark beetles in a climate change perspective, by authorities as well as in research. Furthermore, discussion and research related to the economic profitability of such adaptive measures are almost absent.

In the current study, we assessed the effects of considering bark beetle risk on forest management practices under current climate and climate change conditions. The specific objectives were to 1) Asses the changes in optimal rotation length when the forest management is adapted to the risk of bark beetle damage, 2) Estimate the economic gains in terms of net present value (NPV) under such adaptation strategy, and 3) Determine which forest conditions benefit the most from risk-adapted forest management.

## 2. Methodology

### 2.1. Outline

First, we constructed a set of hypothetical forest stands that cover forest conditions relevant for the model (Section 2.2). Then, for each forest stand, we generated and simulated the forest development under alternative harvest schedules having different rotation lengths (Section 2.3). Initially, we calculated the NPV of each schedule, assuming no bark beetle damage. Then, using Seidl et al. (2009) models (Section 2.4), we estimated the probabilities and intensities of bark beetle damage for each schedule, using all combinations of mean temperatures from 0.1 to 15 °C and annual precipitation between 500 and 2000 mm. After estimating bark beetle risks, we recalculated the NPV values and optimal rotation lengths by factoring in the risk of bark beetle damage (Section 2.5). Finally, we used the climatic conditions (temperature and precipitation) specific to some selected regions of interest in Norway to illustrate and compare potential impacts on optimum rotation length and economic gains (Section 2.6). The R code supporting this research can be accessed at [https://github.com/JoyRomeiro/barkbeetlerisk.git].

### 2.2. Stand data

A total of 300 hypothetical forest stands, each covering 1 hectare, were constructed to represent a wide range of forest conditions relevant for modeling bark beetle probability and damage intensity (see models from Seidl et al. 2009, Appendix 1). The three most important explanatory variables of these models are stand age, stand density (stocking density relative to fully stocked yield table stands) and Norway spruce share (number of Norway spruce trees per hectare relative to the total number of trees per hectare) (Table 1). Stand characteristics were derived from Norwegian yield tables for Norway spruce (Braastad, 1975; Tveite, 1977), covering five site index (SI) classes that reflect forest productivity. These classes were defined by H40 values of 23 m, 20 m, 17 m, 14 m, and 11 m, where H40 represents the dominant height of trees at 40 years of breast height age (Tveite, 1977).

Initially, we created a basic set of 50 stands. For each SI class, 10 stands were evenly distributed by age, ranging from the youngest stands—at an age when dominant height reached approximately 10 m—to the oldest stands corresponding to the maximum mean annual increment (MAI). These maximum MAI ages were 70, 80, 90, 100, and 110 years for site indices H40 of 23, 20, 17, 14, and 11 m, respectively (Braastad, 1975). These oldest stands represent the optimal rotation length under ideal conditions (zero interest rate and no risk), setting an upper boundary for rotations. Relative age, calculated as the stand's actual age divided by its age of maximum MAI, ranged from about 0.35 to 1.0 across all SI classes. Stands with relative ages below 0.6 were classified as "young," while those above 0.6 were classified as "old." *Ips typographus* typically attacks older Norway spruce trees with thicker bark, which provides shelter for adult beetles and sufficient nutrients for offspring development (Honkaniemi et al., 2018). Consequently, susceptibility to bark beetle attacks increases with stand age.

All 50 basic stands initially had high relative density and high Norway spruce share, meaning they were densely stocked and composed entirely of Norway spruce, but to examine the impact of varying density and species composition, we expanded the dataset to include additional scenarios. Relative tree density (RD) was calculated using the Hart-Becking index (S%), defined as:

$$RD = \frac{10}{S\%} \tag{1}$$

where:

$$S\% = \sqrt{\left(\frac{10000}{N}\right)\Big/ H_0} * 100$$

$N$ = number of trees/ha and $H_0$ = dominant height (m). The Hart-Becking index assumes that self-thinning starts when S% reaches 10%, indicating the upper limit for stand density.

Norway spruce share was based on the number of trees per hectare, and we assumed three different levels (high, medium and low): 100% Norway spruce, 50% Norway spruce (and 50% Scots pine) and 10% Norway spruce (and 90% Scots pine). In addition to the basic 50 stands characterized as stands with "High relative density"/"High Norway

**Table 1**
Properties of 300 hypothetical stands in the simulation by five site index levels (23, 20, 17, 14, 11), ten stand ages for each index (e.g., for site index 23: 25, 30, 35, 40, 45, 50, 55, 60, 65, 70), two relative density levels (High, Low), and three Norway Spruce share levels (100%, 50%, 10%).

| Site index ($H_{40}$, m) | Age (years) | | Relative density | | | | Norway spruce share (%) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | Min-Max | High | | Low | | High | Medium | Low |
| | | | Mean | Min-Max | Mean | Min-Max | | | |
| 23 | 48 | 25–70 | 0.86 | 0.52–1.01 | 0.69 | 0.42–0.80 | 100 | 50 | 10 |
| 20 | 55 | 27–82 | 0.86 | 0.46–0.95 | 0.71 | 0.38–0.77 | 100 | 50 | 10 |
| 17 | 62 | 32–92 | 0.83 | 0.47–0.90 | 0.70 | 0.39–0.75 | 100 | 50 | 10 |
| 14 | 71 | 38–103 | 0.75 | 0.42–0.82 | 0.65 | 0.36–0.72 | 100 | 50 | 10 |
| 11 | 78 | 45–110 | 0.66 | 0.38–0.72 | 0.57 | 0.32–0.64 | 100 | 50 | 10 |

spruce share", we constructed five similar sets of stands (50 stands in each set) characterized as stands with "High relative density"/"Medium Norway spruce share", "High relative density"/"Low Norway spruce share", "Low relative density"/"High Norway spruce share", "Low relative density"/"Medium Norway spruce share", and "Low relative density"/"Low Norway spruce share". Table 1 displays a summary of the key properties of the 300 stands.

### 2.3. Simulation

The simulations were carried out using the forest simulator GAYA 2.0 (Strîmbu et al., 2023). The simulator explores possible future states of a forest stand by applying different silvicultural treatments over a planning horizon. The model is based on stand-level attributes like basal area, number of trees, dominant and mean height, stand age, etc., and can simulate the development for the three main species in Norway: spruce, pine, and birch, for mono-species as well as mixed-species single-layered forest stands. The simulation generates a set of treatment schedules with corresponding cash flows of costs and incomes that are summarized as a monetary net present value (NPV) based on a preset yearly discount rate. The results are presented in Norwegian Krone (NOK), which converts to Euro as 1 NOK = 0.083 EUR as per 07.04.2025. The simulations are controlled by parameters that include the number of periods, period length, prices per m$^3$ of timber and pulp, and cost rates for different types of harvest and silvicultural work. The model calculates the NPV assuming management continuity beyond the planning horizon timeframe.

For this study, we simulated 12 periods of 5 years each and applied a discount rate of 3%. For this study we wanted, as much as possible, to maintain the initial stand characteristics as described in Section 2.2 over time and restricted the treatment options in each period to let grow (do nothing) and final harvest, i.e. thinning was not allowed. This means that changes over time in species composition and density only take place due to the intrinsic properties of the growth and mortality models.

### 2.4. Risk assessment - bark beetle damage probability and intensity

The bark beetle risk assessment was conducted using the probability and damage intensity models from Seidl et al. (2009). These models were selected because they were found to be a suitable option for forest management planning regarding the inputs required, the ability to estimate probability and intensity of damage, and the possibility to address climate change (M N Romeiro et al., 2022). Although the Seidl et al. models were initially developed based on Austrian conditions, they have been validated under Norwegian conditions and have shown to be suitable for Norway's climate and forest ecosystems (M N Romeiro et al., 2023). Additionally, while Seidl et al. estimated bark beetle damage probability (pBB) and intensity (iBB) for individual years, we adapted their equations to work over 5-year periods. Since bark beetle damage could happen in any of those five years—or not at all—we developed additional calculations to estimate the average damage expected across each full 5-year period.

Let $pBB_i$ and $iBB_i$ be the predicted damage probability and intensity for year $i$. Given 5 consecutive years, there are $2^5 = 32$ different damage configurations. Let $k$ index be the damage configurations. We define a helper function $attack(i,k) = \left\lfloor \frac{k-1}{2^i} \right\rfloor \%2$ that returns 1 if there is damage in the year $i$ of the $k$-th damage configuration or 0 otherwise.

We calculate the probability of damage configuration $k$ as follow:

$$P(k) = \prod_{t=1}^{5} \left[attack(i,k)pBB_i + (1 - bit(i,k))(1 - pBB_i)\right] \tag{2}$$

Similarly, we calculate the combined intensity of damage in configuration $k$:

$$I(k) = 1 - \prod_{i=1}^{5} \left[1 - attack(i,k)iBB_i\right] \tag{3}$$

Let $I_{per}$ be the random variable denoting the damage intensity over the 5-year period. The possible realizations of $I_{per}$ are linked to the 32 possible realizations of damage configurations. The expected value of $I_{per}$ is calculated as:

$$E\left[I_{per}\right] = \sum_{k=1}^{32} P(k)I(k) \tag{4}$$

Let $I_{sch}$ be the random variable denoting the damage intensity for the entire schedule which consists of all the consecutive periods prior to harvest. If there are $p \leq 12$ periods before harvest:

$$I_{sch} = 1 - \prod_{i=1}^{p} \left[1 - I_{per}[i]\right] \tag{5}$$

Since $I_{per}[i]$ are independent for all periods $i \leq p$ (i .e., due to realizations of damage configurations being independent among periods), the expected value of $I_{sch}$ is calculated as:

$$E[I_{sch}] = 1 - \prod_{i=1}^{p} \left[1 - E\left[I_{per}[i]\right]\right] \tag{6}$$

### 2.5. NPV, economic gain and rotation length

For a given forest stand, let $NPV(i)$ be the net present value of the i th schedule under the assumption that there is no bark beetle damage. This value is fixed, without any associated uncertainty. Let $NPV_{BB}(i)$ be the net present value of the i th schedule when damage is possible. $NPV_{BB}(i)$ is a random variable calculated as:

$$NPV_{BB}(i) = \ (1 - I_{sch}(i))NPV(i) \tag{7}$$

We are interested in the expectation of $NPV_{BB}(i)$ which is calculated as:

$$E[NPV_{BB}(i)] = \ (1 - E[I_{sch}(i)])NPV(i) \tag{8}$$

From all possible schedules $i$, two are of interest for further analyses:

1) the schedule $i_{OPT}$ that maximizes $NPV(i)$
2) the schedule $i_{OPT\_BB}$ that maximizes $E[NPV_{BB}(i)]$

$i_{OPT}$ is the schedule with the highest NPV under the assumption that there will be no bark beetle damage. However, when $i_{OPT}$ is evaluated under the risk of bark beetle damage its expected NPV will be lower than that of $i_{OPT\_BB}$: $E[NPV_{BB}(i_{OPT})] \leq E[NPV_{BB}(i_{OPT\_BB})]$. We are interested in estimating the economic gain by considering bark beetle risks in harvest planning. The expected economic gain can be calculated directly by taking the difference between the two expected NPVs:

$$Gain(NOK\,/\,ha) = E[NPV_{BB}(i_{OPT_{BB}})] - E[NPV_{BB}(i_{OPT})] \tag{9}$$

The relative gain was calculated as:

$$Relgain(\%) = 100\ \times \frac{E[NPV_{BB}(i_{OPT_{BB}})] - E[NPV_{BB}(i_{OPT})]}{E[NPV_{BB}(i_{OPT})]} \tag{10}$$

We are also interested in how the optimal rotation length is affected by the bark beetle risk:

$$Optrotdiff = RotationLength(i_{OPT}) - RotationLength(i_{OPT_{BB}}) \tag{11}$$

### 2.6. Areas of interest in Norway in current climate and climate change conditions

We selected five Norwegian regions spanning a variety of climate conditions (Fig. 1). All regions comprise significant areas of Norway

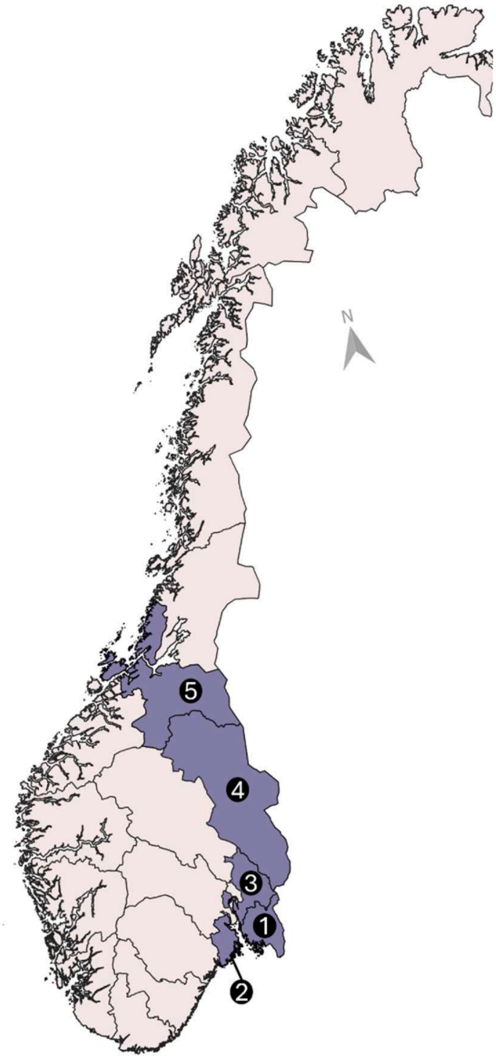

**Fig. 1.** Geographical location of the five selected regions in Norway (1: Østfold; 2: Vestfold; 3: Akershus; 4: Hedmark; 5: Sør-Trøndelag).

spruce dominated forest. The current climate conditions per each region were extracted from Harris et al. (2020) from the 1991–2020 period. To account for climate change, the projected increase in temperature and precipitation based on Hanssen-Bauer et al. (2017) were added to the current temperature and precipitation to reflect the potential situation in the 2071–2100 period (Table 2).

When analyzing bark beetle risk, mean annual temperatures for current climate and climate change scenarios RCP4.5 and RCP8.5 were rounded to the nearest integer. Similarly, annual precipitation values were rounded to the nearest hundred. For instance, when assessing the difference in rotation length and NPV gain for Østfold, we employed a mean annual temperature of 6 °C (rounding from the actual 6.4 °C) and an annual precipitation of 900 mm (rounding from 876 mm) as our input parameters (Table 2).

## 3. Results

### 3.1. NPV gain and rotation length difference

For stands that had an initial age close to the age of maximum MAI, factoring in bark beetle risk was irrelevant, because the optimal strategy when maximizing NPV consistently meant that the stand would be harvested in the first period, regardless of risk assessments. This finding was consistent across the two oldest stands within each SI classes, across various combinations of Norway spruce shares and stand densities, totaling 60 stands. Those 60 stands were then excluded from further analysis. Furthermore, at a 10% Norway spruce share, both rotation length difference and economic gain are substantially low, with average rotation difference as low as 0.8 years (range 0 – 15) and average economic gain as 75 NOK/ha (range 0 – 5402), irrespective of density. Due to these markedly smaller values, the 10% Norway spruce share scenarios were also excluded from further detailed analysis, leaving the final analysis with 160 stands (Table 3).

When considering all climatic conditions (annual temperature and annual precipitation from 0.1 to 15 °C, and 500 to 2000 mm, respectively), low density stands with 100% Norway spruce presented an average rotation length difference of 4 years (range 0 – 25) and the highest NPV gain of 1440 NOK/ha (range 0 – 56,446). As Norway spruce share decreases, there is a decrease in both rotation difference and economic gain, regardless of stand density (Table 3).

Old stands present a rotation length difference of 2.4 years (range 0 – 25) and a gain of 1124 NOK/ha (range 0 – 56,446) in average, while young stands present a greater rotation length difference of 3.8 years (range 0 – 25) but a lower gain of 768 NOK/ha (range 0 – 33,924) (Table 4). When examining stands across different Site Index (SI) classes, the lowest gain is seen at SI class $H_{40} = 11$ m, with a value of 626 NOK/ha (range 0 – 27,475), whereas the greatest gain is at SI class $H_{40} = 23$ m, amounting to 1359 per NOK/ha (range 0 – 56,446).

Central to our analysis, Fig. 2 and 3 show the core findings for how

**Table 3**
Average rotation length difference and gain in NPV from considering bark beetle risk in forest management, per Norway spruce share and stand density. Mean annual temperature and annual precipitation used range from 0.1 to 15 °C, and 500 to 2000 mm, respectively.

| Norway spruce share | Density | No. of stands | Rotation length difference (years) | Gain (NOK/ha) |
|---|---|---|---|---|
| 100% | Low | 40 | 4 (0 – 25) | 1440 (0 – 56,446) |
| 50% | Low | 40 | 3 (0 – 20) | 564 (0 – 20,430) |
| 100% | High | 40 | 3.5 (0 – 25) | 1356 (0 – 48,225) |
| 50% | High | 40 | 2 (0 – 20) | 423 (0 – 17,007) |

**Table 2**
Average annual temperature and precipitation for current (1991–2020) and projected climate scenarios (2071–2100) under RCP4.5 (moderate emissions) and RCP8.5 (high emissions) for regions of interest in Norway.

| Region | Current Climate | | RCP 4.5 | | RCP 8.5 | |
|---|---|---|---|---|---|---|
| | Mean annual temp. ( °C) | Annual precip. (mm) | Mean annual temp. ( °C) | Annual precip. (mm) | Mean annual temp. ( °C) | Annual precip. (mm) |
| stfold | 6.4 | 876 | 8.7 | 929 | 10.8 | 972 |
| Vestfold | 6.3 | 1008 | 8.6 | 1089 | 10.7 | 1159 |
| Akershus | 5.1 | 841 | 7.4 | 908 | 9.5 | 967 |
| Hedmark | 1.7 | 681 | 4.0 | 735 | 6.1 | 783 |
| Sør-Trøndelag | 2.9 | 1008 | 5.3 | 1119 | 6.4 | 1220 |

**Table 4**
Average rotation length difference and gain in NPV from considering bark beetle risk in forest management, per age category and site index. Mean annual temperature and annual precipitation used range from 0.1 to 15 °C, and 500 to 2000 mm, respectively.

| Stand category | No. of stands | Rotation length difference (years) | Gain (NOK/ha) |
|---|---|---|---|
| Old | 80 | 2.4 (0 – 25) | 1124 (0 – 56,446) |
| Young | 80 | 3.8 (0 – 25) | 768 (0 – 33,924) |
| SI = 23 m | 32 | 2.7 (0 – 25) | 1359 (0 – 56,446) |
| SI = 20 m | 32 | 2 (0 – 20) | 797 (0 – 48,225) |
| SI = 17 m | 32 | 3.6 (0 – 20) | 991 (0 – 47,612) |
| SI = 14 m | 32 | 4 (0 – 25) | 955 (0 – 38,901) |
| SI = 11 m | 32 | 3.5 (0 – 25) | 626 (0 – 27,475) |

changes in optimal rotation length and NPV gain, respectively, are influenced by temperature and precipitation under different conditions of stand density (low and high), stand age (young and old), and Norway spruce share (50% and 100%). For example, by referencing the temperature and precipitation data presented in Table 2, we can determine the adjustments forest owners in Østfold should make to their rotation lengths (Fig. 2) and the potential economic gain (Fig. 3) they would get from such adjustment. Currently, Østfold experiences a mean temperature of 6.4 °C and annual precipitation of 876 mm. For a forest owner with a young, low-density stand with 100% Norway spruce, it is advisable to reduce the rotation length by approximately 2.5 years, potentially resulting in an economic gain of 100 – 250 NOK/ha.

The greatest average economic gain when considering bark beetle risk in forest management is 27,220 NOK/ha (>20,000 in Fig. 3) in old low-density 100% Norway spruce stands where mean annual temperature is 15 °C and annual precipitation is 500 mm (Fig. 3). To get such economic gains, rotation length would need to be reduced by 10 years in average (Fig. 2). Similarly, reduction in rotation length is particularly large for younger stands; young low-density 100% Norway spruce stands, where mean annual temperature is 15 °C and annual precipitation is 500 mm, should be harvested in average 22 years earlier (Fig. 2) than usual with a gain in between 10,000 and 20,000 NOK/ha (Fig. 3).

### 3.2. Areas of interest in current climate and climate change scenarios

In Norway, Østfold, Vestfold, and Akershus are the regions with the greatest economic gains from incorporating bark beetle risk into forest management under the current climate. Østfold leads with an average gain of 110 NOK/ha when reducing rotation length by 2 years (Table 5), reaching up to an average of 195 NOK/ha (from 0 to 598 NOK/ha) in old, low-density stands with 100% Norway Spruce, when harvesting 2.8 years earlier than when not considering risk (Table 6). Vestfold shows an average gain of 88 NOK/ha for harvesting 1.8 years earlier, with gains up to an average of 154 NOK/ha in young, low density stands with 100% Norway spruce, but this benefit could increase to as much as 480 NOK/ha for stands with SI class $H_{40}$ 23 m. Akershus has a lower average gain of 47 NOK/ha for a 1.5-year reduction in rotation length, going up to an average of 103 NOK/ha (from 0 to 331 NOK/ha) in young, low-density stands with 100% Norway Spruce.

If climate changes according to scenario RCP 4.5, between 2071 and 2100, managed forests would need a reduction in rotation length ranging from 1 year in Hedmark with a gain of 13 NOK/ha to 4 years in Østfold with a gain of 686 NOK/ha (Table 7). However, if climate changes according to RCP 8.5, the required shortening of rotation lengths would extend from 1.7 years in Sør-Trøndelag to 5.5 years in Østfold with gains of 61 NOK/ha and 1195 NOK/ha, respectively (Table 8).

## 4. Discussion

### 4.1. NPV gain and rotation length difference for all climatic conditions

Not surprisingly, our findings show that forest stands with a higher proportion of Norway Spruce present more significant benefits from incorporating bark beetle risk into their management strategies. This benefit is expressed in the form of greater rotation length difference and NPV gain (Table 3). Similarly, with a Norway spruce share of 10%, both the rotation length difference and the economic gain are markedly low. This led us to decide not to include them in further analysis, because adapting forest management to mitigate bark beetle risk is only useful in areas where bark beetle damage is significant.

Additionally, older stands show greater NPV gains, which can be explained by the larger volume of timber harvested within a few years. Younger stands, on the other hand, are the ones where rotation is shortened the most (Table 4). Older stands have limited room for shortening rotation periods, and the oldest stands initially considered in this paper were often best suited for immediate harvest. Consequently, we excluded stands with age close to their maximum MAI from further analyses, focusing instead on those where rotation adjustment is a relevant option.

Lower stock density presented larger NPV gains and rotation length differences. This can be explained by the model's assumption that lower stock density increases sunlight level within the canopy, which in turn increases bark beetle numbers (Seidl et al., 2007). Regarding site index, stands in SI class $H_{40} = 11$ m yield the lowest NPV gains, whereas those in SI class $H_{40} = 23$ m achieve the greatest economic gains.

It is important to point out that Table 3 and 4 present mean values for the whole climatic range (from 0.1 - 15 °C for mean temperature and from 500 – 2000 mm for annual precipitation). Those values are presented to show how, in general, NPV gain and rotation length difference behave for different forest conditions (Norway spruce share, stand age, density and site index). Therefore, for any specific temperature and precipitation condition, the conclusions can best be drawn from Fig. 2 and 3. For example, when considering climatic conditions typical of European regions with significant bark beetle damage, such as the Czech Republic, Germany, and Austria - mean annual temperatures ranging from 8–10 °C and annual precipitation between 600–800 mm. Norway Spruce monocultures should have their rotation length shortened by an average of 6.7 years when compared to when bark beetle risk is not considered in forest management. This would mean an average gain of 2103 NOK/ha for forest owners.

### 4.2. Areas of interest in current climate and climate change scenarios

In the present study we found that, for the current climate conditions, forest owners managing young, low-density Norway spruce stands in Vestfold can achieve an economic benefit of 154 NOK/ha by opting to harvest 2.3 earlier than usual (Table 6). It is crucial to note that Vestfold, the region in question, previously endured significant bark beetle infestations in the 1970–80 s, which, along with windthrows and droughts, led to a loss of 5 million $m^3$ of timber. The bedrock and soil properties in Vestfold, may also predispose stands to drought stress, increasing their susceptibility to bark beetle damage. However, our model does not account for other natural disturbances like windthrows and droughts that could trigger such outbreaks.

Furthermore, the implications of climate change increase the relevance of including bark beetle risk in forest management strategies. For example, RCP 4.5 projections suggest that, in 50 years from now (2071–2100), the rotation length in Vestfold should be shortened by an average of 3.4 years. This adjustment is expected to produce an economic gain three times larger than under current climate conditions. Under the more severe RCP 8.5 scenario, the region would see an average rotation length difference of 4.4 years, corresponding to a five (5.5) times the economic gain of current climate.

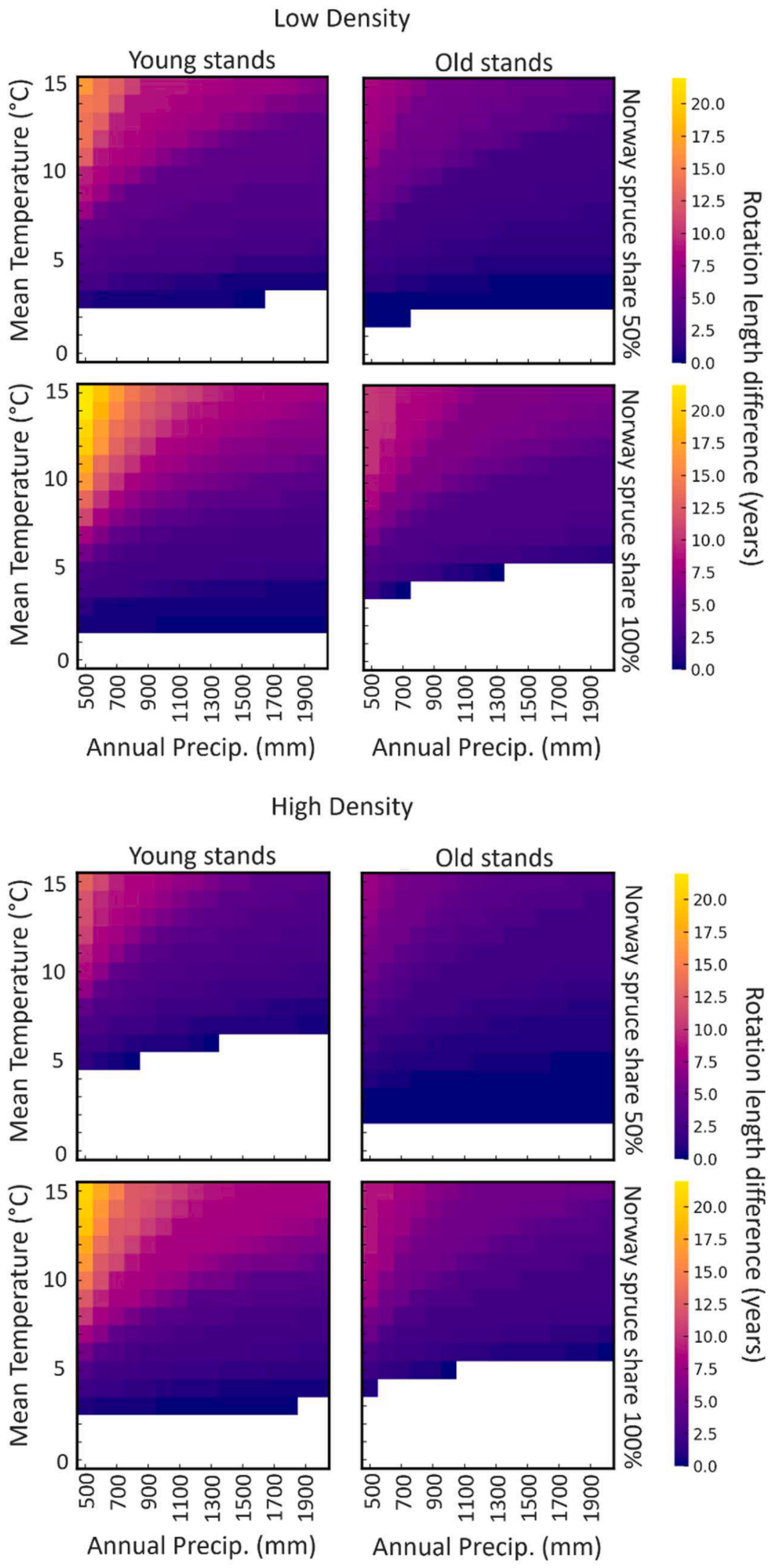

**Fig. 2.** Average optimal rotation length difference (years) when considering all combinations of annual precipitation (from 500 to 2000 mm) and mean temperature (from 0.1 to 15 °C) per Norway spruce share values (50% and 100%), young and old stands, and low and high stand density.

Similar trends are observed in other regions of Norway, such as Østfold, where the recommended reduction in rotation length by 2 years under current conditions could lead to an NPV increase of 110 NOK/ha. In 50 years, under the RCP 4.5 scenario, a reduction in rotation length by 4 years could yield an average gain of 686 NOK/ha. This represents a doubling in rotation length reduction and more than a sixfold increase in NPV gain compared to current conditions. In scenarios of more severe climate change (RCP8.5), this could mean reducing rotation length in 5.5 years and achieving a tenfold increase in NPV gain relative to the present.

It is worth noting that we encountered some variations in the gains that were not directly related to differences in studied conditions (see

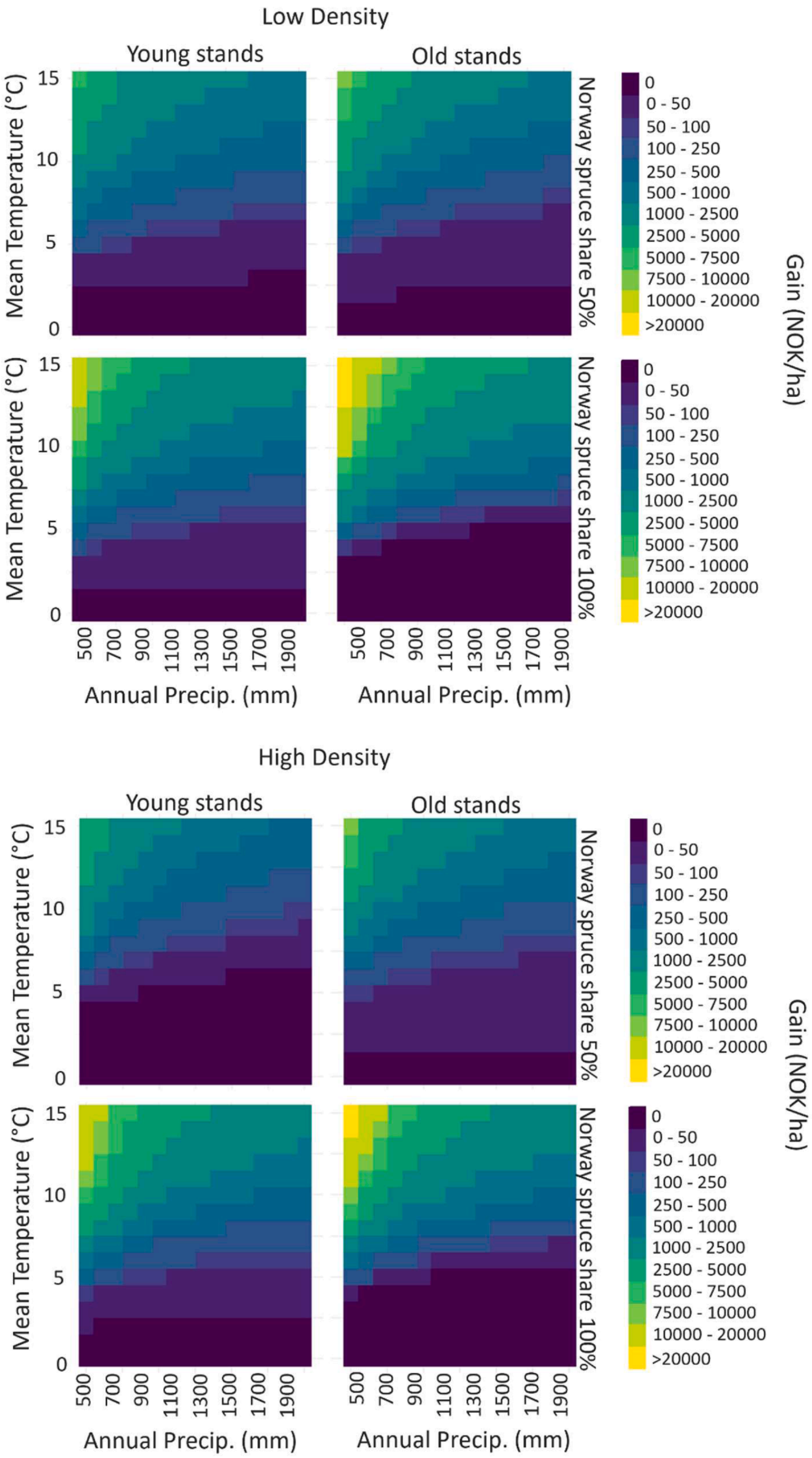

**Fig. 3.** Average gain (NOK/ha) when considering all combinations of annual precipitation (from 500 to 2000 mm) and mean temperature (from 0.1 to 15 °C) per Norway spruce share values (50% and 100%), young and old stands, and low and high stand density.

Appendix 2), but maybe due to the properties of the problem formulations or the nature of simulations. An example of this is shown in Table 6, where old stands with high density and a 50% Norway spruce share in Hedmark and Sør-Trøndelag show NPV gains of 1 NOK/ha and 3 NOK/ha respectively, which are unexpectedly high, compared to the other conditions for such forest and climatic conditions. However, when unusual high NPV gains due to the nature of simulations are experienced, other stands might experience unusually low gains for similar reasons.

### 4.3. *Forest management in the face of bark beetle risk*

Since bark beetle risk changes greatly with stand age, those risks are important factors to consider when determining optimal forest rotation

**Table 5**

Average of gain (NOK/ha) and rotation length difference per region of interest, with maximum and minimum values in parenthesis in current climate (1991–2020).

| Region | Mean annual temperature ( °C) | Annual precipitation (mm) | Rotation length diff. (years) | Gain (NOK/ha) |
|---|---|---|---|---|
| stfold | 6.4 | 876 | 2 (0–10) | 110 (0–671) |
| Vestfold | 6.3 | 1008 | 1.8 (0–10) | 88 (0–607) |
| Akershus | 5.1 | 841 | 1.5 (0–10) | 47 (0–452) |
| Hedmark | 1.7 | 681 | 0.1 (0–5) | 0 (0–20) |
| Sør-Trøndelag | 2.9 | 1008 | 0.2 (0–5) | 1 (0–75) |

**Table 6**

Average of NPV gain (NOK/ha) and rotation age difference (years) for all five regions in current climate (1991–2020).

| Young stands | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Norway spruce share (%) | Density | Regions | | | | | | | | | |
| | | stfold | | Vestfold | | Akershus | | Hedmark | | Sør-Trøndelag | |
| | | Gain (NOK/ha) | Rot. diff. (years) | Gain (NOK/ha) | Rot. diff. (years) | Gain (NOK/ha) | Rot. diff. (years) | Gain (NOK/ha) | Rot. diff. (years) | Gain (NOK/ha) | Rot. diff. (years) |
| 100 | high | 140 | 2.3 | 120 | 2.3 | 72 | 2.3 | 0 | 0 | 0 | 0.3 |
| 100 | low | 179 | 2.5 | 154 | 2.3 | 103 | 2.3 | 0 | 0.5 | 4 | 0.5 |
| 50 | high | 10 | 0.8 | 7 | 0.8 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| 50 | low | 103 | 3 | 87 | 2.8 | 55 | 2.5 | 0 | 0 | 1 | 0.5 |
| Old stands | | | | | | | | | | | |
| Norway spruce share (%) | Density | Regions | | | | | | | | | |
| | | stfold | | Vestfold | | Akershus | | Hedmark | | Sør-Trøndelag | |
| | | Gain (NOK/ha) | Rot. diff. (years) | Gain (NOK/ha) | Rot. diff. (years) | Gain (NOK/ha) | Rot. diff. (years) | Gain (NOK/ha) | Rot. diff. (years) | Gain (NOK/ha) | Rot. diff. (years) |
| 100 | high | 105 | 1.8 | 70 | 1.5 | 16 | 0.8 | 0 | 0 | 0 | 0 |
| 100 | low | 195 | 2.8 | 146 | 2.5 | 57 | 2 | 0 | 0 | 0 | 0 |
| 50 | high | 61 | 1 | 51 | 0.8 | 33 | 0.8 | 1 | 0.3 | 3 | 0.3 |
| 50 | low | 81 | 1.8 | 67 | 1.5 | 36 | 1.5 | 0 | 0.3 | 2 | 0.3 |

**Table 7**

Average of gain (NOK/ha) and rotation length difference per region of interest, with maximum and minimum values in parenthesis for RCP4.5 (for years 2071 and 2100).

| Region | RCP4.5 | | | |
|---|---|---|---|---|
| | Mean annual temperature ( °C) | Annual precipitation (mm) | Rotation length difference (years) | Gain (NOK/ha) |
| stfold | 8.7 | 929 | 4 (0–10) | 686 (0–3661) |
| Vestfold | 8.6 | 1089 | 3.4 (0–10) | 475 (0–2552) |
| Akershus | 7.4 | 908 | 2.5 (0–10) | 242 (0–1283) |
| Hedmark | 4 | 735 | 1 (0–10) | 13 (0–268) |
| Sør-Trøndelag | 5.3 | 1119 | 1.2 (0–10) | 21 (0–335) |

**Table 8**

Average of gain (NOK/ha) and rotation length difference per region of interest with maximum and minimum values in parenthesis for RCP8.5 (for years 2071 and 2100).

| Region | RCP8.5 | | | |
|---|---|---|---|---|
| | Mean annual temperature ( °C) | Annual precipitation (mm) | Rotation length difference (years) | Gain (NOK/ha) |
| stfold | 10.8 | 972 | 5.5 (0–15) | 1195 (0–5613) |
| Vestfold | 10.7 | 1159 | 4.4 (0–10) | 861 (0–4297) |
| Akershus | 9.5 | 967 | 4.3 (0–10) | 837 (0–4280) |
| Hedmark | 6.1 | 783 | 2.2 (0–10) | 142 (0–804) |
| Sør-Trøndelag | 6.4 | 1220 | 1.7 (0–10) | 61 (0–515) |

length. A shorter rotation period can substantially reduce damage caused by bark beetles (Björkman et al., 2015). For example, Zimová et al. (2020) found that in Central Europe, an even-aged management regime with a 60-year rotation period resulted in an 11.5% decrease ($m^3$/ha/year) in bark beetle damage, compared to the standard 100-year rotation currently practiced.

Older forests not only face a direct threat from bark beetles but also suffer from an indirect risk linked to wind damage, which also increases as the forest ages. Windthrow risk is mentioned as one of the greatest motivators for adopting shorter rotation periods (Björkman et al., 2015). This is because windthrow events, apart from the direct damages, can significantly increase trees' susceptibility to bark beetle outbreaks (M N Romeiro et al., 2022). Consequently, some studies assess rotation length change to tackle bark beetle and wind damage risks together (Dobor, Hlásny, and Zimová, 2020). However, the current study could not account for interactions that might increase susceptibility to bark beetle infestation, such as wind damage and drought conditions, because the model used to predict bark beetle damage (Seidl et al., 2009) does not include these factors. Incorporating these additional factors would require a new study when suitable models become available.

Other natural disturbance risks would also be decreased by a shorter rotation length. When looking at wind damage alone, a rotation age of 60 years instead of 100 years would decrease in 18% the damage ($m^3$/ha/year) caused by wind (Zimová et al., 2020). Root rot risk can also be reduced by shortening the rotation length, although this effect is less pronounced than what we found in our current study. For instance, a root rot case study in Norway showed that 14% of the stands would benefit from earlier harvesting, with most having their rotation length shortened by only 1 or 2 years (Aza et al., 2021). That can be explained by the slow spread rate of root rot compared to the value growth compensating for the loss, as opposed to natural disturbances such as windthrow and bark beetle damages where the effects emerge faster and cannot be compensated with a growth in healthy trees.

However, a reduction in rotation length is no ultimate answer for dealing with natural disturbances, since there are also negative effects that may come with a shorter rotation length, such as a decrease in carbon storage and fewer large trees in the forest (Zimová et al., 2020). Therefore, other forest management measures should also be applied when trying to avoid the economic losses caused by bark beetles. Tree species composition is an important variable for bark beetle risk, as seen in the differences of rotation lengths and economic gains between stands with 100% and 50% spruce trees. Therefore, a change to more diverse stands with higher proportion of less vulnerable trees, would help decrease those risks of damage (Dobor, Hlásny, and Zimová, 2020; Gohli et al., 2024; Sebald et al., 2021), as well as increase the provisioning of ecosystem services (Mori, 2017). For example, spruce–birch and spruce–pine mixtures are said to be one of the key management practices to combat bark beetles in Sweden (Felton et al., 2023). Moreover, continuous cover forestry is recommended over clear-cutting to reduce bark beetle attacks by minimizing tree exposure to stressors (Gohli et al., 2024).

In Europe, managing high-risk or active bark beetle outbreaks typically involves the removal of windthrown or infested trees, along with healthy trees near infected areas—a practice known as sanitation and salvage logging (Dobor, Hlásny, Rammer, et al., 2020b). This approach is generally considered effective in controlling beetle outbreaks if over 95% of the windthrown spruce trees are removed (Dobor, Hlásny, Rammer, et al., 2020a). However, improper execution of these methods can lead to significant ecological impacts, including increased erosion, flooding, avalanche risks, heightened vulnerability to wind damage at forest edges, and changes in forage availability for herbivores and shelter for predators (Leverkus et al., 2021).

To enhance management strategies further, integrating salvage and sanitation options into risk analysis could be beneficial. This would require a two-phase optimization approach: initially making decisions under uncertainty to determine whether to plan for sanitation or salvage cuttings, followed by making specific decisions in the second phase based on updated information once new data on damage becomes available. Such a strategy would be more effective if the probability models included a spatial component, accounting for how bark beetle spread depends on prior infestations, rather than assuming independent attacks as we currently do. This would also allow for calculating the value of information regarding new attacks, providing forest managers with better tools to optimize their responses and minimize potential economic losses.

Recent monitoring in Southern Norway has shown a rise in bark beetle numbers, with evidence suggesting they can now complete two generations each year (Økland et al., 2021). In response, the Norwegian Agriculture Agency (Landbruksdirektoratet, 2021) has initiated some preliminary actions as part of a preparedness plan to address bark beetle challenges. Most operative measures are relatively short-term for situations in which the probability of an outbreak is high, or the outbreak has already started. This includes measures such as identification and prioritization of potential areas for harvest (susceptive to drought, windthrow, vulnerable stand edges), preparedness measures for machines and identification and removal of already attacked trees. Some long-term measures related to silvicultural practices are also mentioned in the preparedness plan: e.g., changes in tree species during regeneration to promote a more diverse forest structure and applying harvest methods that support tree species and size diversity. Additionally, an increase in thinning intensity is also mentioned in the preparedness plan. However, there is debate in the literature over thinning. Some studies advocate for increased thinning to increase trees' vigor by reducing competition for resources (Hlásny et al., 2021b; Jakuš et al., 2011), while others suggest less thinning, since the practice can increase the likelihood of storm and root rot damage, which would then increase the risk of bark beetle damage (Subramanian et al., 2016).

## 5. Conclusions

The current study highlights the importance of integrating bark beetle risk into forest management strategies. Old, low density stands with a high proportion of Norway Spruce, located in more productive sites, experience significant economic benefits from management adjustments involving earlier harvest. The extent to which the rotation length should be shortened varies considerably, depending on factors such as the forest's current age, site productivity, and the proportion and density of Norway Spruce. In regions like Vestfold, Norway, where bark beetle infestations are common, early harvesting can provide substantial economic benefits, particularly under projected climate change conditions over the next 50 years. In the most severe climate change scenario, forest owners in Vestfold could see nearly tenfold economic gains from reducing rotation lengths compared to the current climate. This highlights the critical need for adaptive management practices in response to climate change impacts.

Despite our model not accounting for interactions between different natural disturbances, there is an obvious need for a more holistic approach to forest management, considering additional natural disturbances, such as windthrow and drought, in management decisions. The adaptation includes not only adjusting rotation lengths but also diversifying tree species composition to enhance forest resilience against bark beetle infestations as well as other environmental stressors.

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## CRediT authorship contribution statement

**Joyce M.N. Romeiro:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Victor F. Strîmbu:** Writing – original draft, Validation, Software, Methodology. **Tron Eid:** Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Annika Kangas:** Supervision, Investigation, 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.

## Appendix 1. Models of bark beetle probability and damage intensity

The following equations from Seidl et al. (2009) were used to calculate pBB:

$$pBB_i = \frac{e^{Z_{j\mu mn}}}{1 + e^{Z_{jkmn}}}$$

$$Z_{ijklm} = B0 + B1 \cdot \text{ LogTemp }_j$$

$$+B2 \cdot \text{ LogPrecip }_k + B3 \cdot \text{ Age }_l$$

$$+B4 \cdot \text{ Density }_m + B5 \cdot \text{ Share }_n$$

$$+B6 \cdot \left(\text{LogTemp} \cdot \text{LogPrecip }_{jk}\right)$$

$$+B7 \cdot (\text{ LogTemp} \cdot \text{Age })_{jl}$$

$$+B8 \cdot \left(\text{LogTemp} \cdot \text{Density }^2{}_{jm}\right)$$

$$+B9 \cdot (\text{ LogTemp} \cdot \text{Share })_{jn}$$

$$+ \text{ B10 } \cdot (\text{ LogPrecip} \cdot \text{Age })_{kl}$$

$$+\text{B11} \cdot (\text{LogPrecip} \cdot \text{Density})_{km}$$

$$+B12 \cdot (\text{ LogPrecip} \cdot \text{Share })_{kn} + \varepsilon_{jk/mn}$$

where: pBB – probability of bark beetle damage
$\mathrm{Z}_{\mathrm{ijklm}}$ – linear combination of predictor variables
$B0$ – intercept
$\mathrm{LogTemp}_{\mathrm{i}}$ – logarithmic mean annual temperature
$\mathrm{LogPrecip}_{\mathrm{j}}$ – logarithmic annual precipitation
$\mathrm{Age}_{\mathrm{k}}$ – stand age
$\mathrm{Density}_{\mathrm{l}}$ – stocking density relative to fully stocked yield table stands
$\mathrm{Share}_{\mathrm{m}}$ – Norway spruce share
$\mathrm{E}_{\mathrm{ijklm}}$ – error term

The following equations were used to calculate iBB:

$$i\mathrm{BB} = \frac{1}{1 + e^{3.9725 - 2.9673 * SHI}}$$

$$SHI = SEE * SMI * HTS$$

$$SMI_{ij} = B0 + B1 * Temp_i + B2 * Precip_j^{-2} + B3 * \left(Temp * Precip^{-2}\right)_{ij} + E_{ij}$$

where: iBB – annually damaged relative stem number
SHI – stand hazard index
SEE – stand edge index
SMI – soil moisture index over the growing season
HTS – Norway spruce share
$\mathrm{Temp}_{\mathrm{i}}$ – mean annual temperature
$\mathrm{Precip}_{\mathrm{j}}^{-2}$ – $(\mathrm{precipitation})^{-2}$
$\mathrm{E}_{\mathrm{ij}}$ – error term

The models from Seidl et al. (2009) were originally fitted using mean annual temperatures ($\mathrm{Temp}_{\mathrm{i}}$) varying from 2 to 15 °C and annual precipitations ($\mathrm{Precip}_{\mathrm{j}}$) varying from 500 to 2000 mm. For stand age ($\mathrm{Age}_{\mathrm{k}}$), the model of probability of bark beetle damage was fitted using stands from 40 to 120 years old. Stocking density ($\mathrm{Density}_{\mathrm{l}}$) is defined as the basal area of a stand relative to the basal area of a fully stocked stand as given in the respective local yield tables (Seidl et al., 2009), and they were originally tested using values from 0.6 to 1.0. Norway spruce share ($\mathrm{Share}_{\mathrm{m}}$) is used as a categorical variable with three levels (10%, 50%, and 100%) that represent the percentage of number of trees. For the damage intensity model, stand edge index (SEE) was kept as 1.

The parameters for the bark beetle probability model and for the soil moisture index regression model, as well as their respective standard errors, were retrieved from Seidl et al. (2009) and are presented in Tables A1 and A2.

**Table A1**
Parameters and standard errors of the parameter estimates of the bark beetle probability model.

| Parameter | Description | Parameter Value | Standard error |
|---|---|---|---|
| B1 | Mean annual temperature (log) | 4.234 | 0.0123 |

(*continued on next page*)

**Table A1** (*continued*)

| Parameter | Description | Parameter Value | Standard error |
|---|---|---|---|
| B2 | Annual precipitation (log) | −1.196 | 0.00531 |
| B3 | Stand age | −0.0433 | 0.000142 |
| B4 | Stocking density | 0.658 | 0.0249 |
| B5 (dummy 50%) | Norway spruce share | −1.425 | 0.0107 |
| B5 (dummy 100%) | Norway spruce share | −2.606 | 0.0104 |
| B6 | Interaction temp * precip | −0.214 | 0.00171 |
| B7 | Interaction temp * stand age | −0.000383 | 0.0000239 |
| B8 | Interaction temp * density | −0.0527 | 0.00417 |
| B9 (dummy 50%) | Interaction temp * spruce share | 0.0993 | 0.00183 |
| B9 (dummy 100%) | Interaction temp * spruce share | 0.245 | 0.00178 |
| B10 | Interaction precip * stand age | 0.00746 | 0.0000195 |
| B11 | Interaction precip * density | −0.104 | 0.00341 |
| B12 (dummy 50%) | Interaction precip * spruce share | 0.278 | 0.00146 |
| B12 (dummy 100%) | Interaction precip * spruce share | 0.457 | 0.00143 |
| B0 | Intercept | −0.301 | 0.0371 |

**Table A2**

Parameters and standard errors of the parameter estimates of the soil moisture index regression model.

| Parameter | Description | Parameter Value | Standard error |
|---|---|---|---|
| B1 | Mean annual temperature | 0.00107 | 0.0000967 |
| B2 | (Mean annual precipitation)$^{-2}$ | 25,490 | 574.4 |
| B3 | Interaction temp * precip$^{-2}$ | 8282 | 58.93 |
| B0 | Intercept | −0.0413 | 0.000943 |

## Appendix 2. Relationship between stand 207 and stand 187

The unexpectedly high NPV gains illustrated in Table 6 is particularly due to stand 207.

Using Østfold’s climate for context, and comparing stand 207 with stand 187 (which has the same forest conditions but has a 100% Norway spruce share): without optimization, stand 207 (50% Norway spruce) would have a NPV of 79,220 NOK/ha, with harvest planned in 5 years. Considering bark beetle damage over this period reduces the NPV to 78,529 NOK/ha. However, an optimized schedule avoids this damage by harvesting 5 years earlier, maintaining an NPV of 79,201 NOK/ha since no bark beetle damage would occur, resulting in a gain of 672 NOK/ha. Stand 187, with 100% Norway spruce, under the same conditions but higher bark beetle damage, would have an optimal NPV of 96,628 NOK/ha if harvested in 5 years without considering damage. Factoring in the increased beetle damage reduces it to 95,432 NOK/ha. The best option, harvesting early to avoid damage, yields an NPV of 95,934 NOK/ha, a gain of 502 NOK/ha, which is 170 NOK less than stand 207′s gain. That happens because in stand 207, 79,220 NOK/ha and 79,201 NOK/ha are very similar, but for the first of them we subtract bark beetle damage for 5 years and for the second we do not subtract any damage. This pattern is especially noted for mean temperatures between 2 °C and 8 °C (Fig. A1). It is worth mentioning that just as stand 207 demonstrates unusual NPV high gains due to the nature of simulations, other stands might also experience unusually low gains for similar reasons.

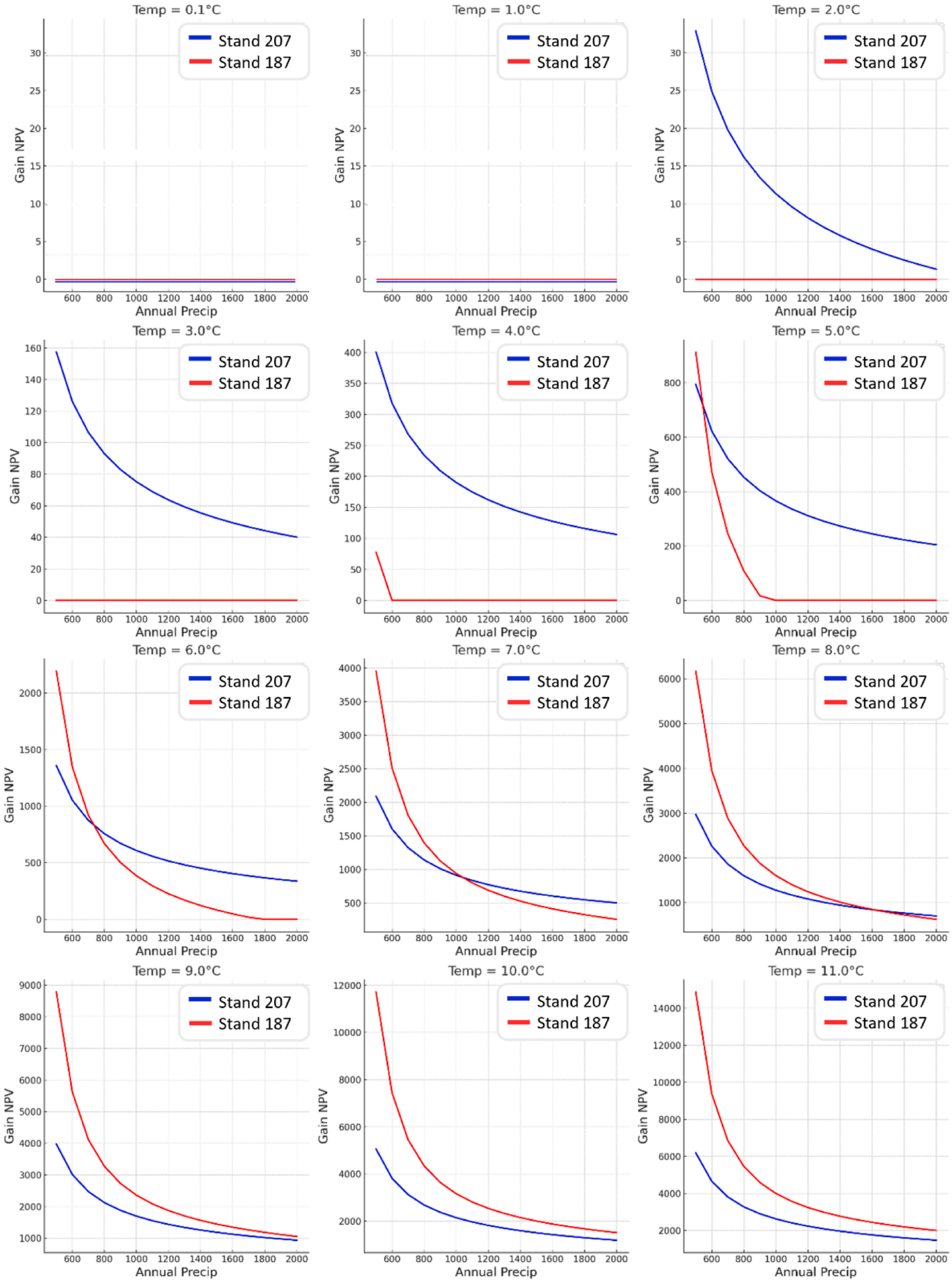

**Fig. A1.** Relationship between NPV gain of two stands, where all forest conditions are identical except for Norway spruce share: Stand 207 has 50% Norway spruce and stand 187 has 100% Norway spruce. Each graph represents a different mean temperature, from 0.1 to 11 °C.

## Data availability

We have included the link to the data and code used in this research within the body of the article

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