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RESEARCH PAPER

Effect of root and butt rot uncertainty on optimal harvest schedules and expected incomes at the stand level

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Abstract

• ***Key message*** **Root and rot (RBR) caused by *Heterobasidion parviporum* Niemelä & Korhonen and *Heterobasidion annosum* (Fr.) Bref. damages Fennoscandian spruce stands. In case the rot infection and its severity are unknown, the mere risk of infection should seldom affect the harvest timing. When it does, the gains by harvesting earlier are minimal.**

• ***Context*** It has been suggested that stands infected by RBR should be harvested earlier than the healthy ones. Yet, we must decide on harvest timing decisions without reliable information on the infection.

• ***Aims*** We studied if harvesting earlier pays off under RBR uncertainty.

• ***Methods*** We structured the uncertainty with a decision tree and calculated the optimal rotations based on expected net present values. We compared rotation lengths to those of healthy stands and calculated gains from earlier harvesting.

• ***Results*** The inclusion of RBR-related uncertainty in the model changed the rotation length of only 14–23% of the stands. The average reduction was 1.3–4.7 years. Yet, the gain from harvesting earlier was too low to be considered.

• ***Conclusion*** In the absence of information on the extent and severity of RBR, it seldom pays off to advance harvests. The value growth in healthy trees tends to compensate for the value reduction due to rot.

Keywords *Heterobasidion parviporum* · *Heterobasidion annosum* · Decision tree · Land expectation value · Economically optimal rotation age

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1 Introduction

The tree pathogens *Heterobasidion parviporum* Niemelä & Korhonen and *Heterobasidion annosum* (Fr.) Bref. causes root and butt rot (RBR) in Fennoscandian coniferous forests, mainly Norway spruce (*Picea abies* L. Karst) and Scots pine (*Pinus sylvestris* L.), in the Northern Hemisphere (Pukkala et al. 2005; Woodward et al. 1998). The infection happens when fresh wood is exposed to the fungi basidiospores, as might occur in areas of clear cut or thinning (Redfern and Stenlid 1998; Rishbeth 1951). Once infected, the mycelia can grow and contaminate neighbouring trees or settle down and be transferred to the next forest rotation (Redfern and Stenlid 1998; Stenlid and Redfern 1998). In Nordic conditions, the decay can reach up to 10–12 m in height (Stenlid and Wästerlund 1986) making RBR particularly harmful as it destroys the most valuable part of the tree, downgrading it from sawn wood quality to pulp or energy wood (Pukkala et al. 2005; Seifert 2007).

Losses due to RBR in spruce forests may constitute a significant challenge to forestry's long-term sustainability in Norway. A nationwide stump survey carried out in 1992 showed that, on average, every 5th harvested spruce in Norway had stem decay caused by *Heterobasidion annosum* (Fr.) Bref. sensu lato (s.l.) (Huse et al. 1994). A probability model for RBR infection in Norway spruce was developed explicitly for Norwegian conditions (Hylen and Granhus 2018).

Literature reveals several models created to estimate the incidence and development of RBR in European countries (e.g. Honkaniemi et al. 2014; Mattila and Nuutinen 2007; Oliva and Stenlid 2011; Pukkala et al. 2005; Seifert 2007; Thor et al. 2007). While this has great potential to assist in the planning process, such models demand accurate information on various parameters that are often uncertain. The result is that forest managers usually overlook uncertainty (Eyvindson and Kangas 2014), using average values for uncertain parameters, which is the same as assuming certainty. In this study, we will consider the definitions used by Eyvindson and Kangas (2014), where the term "uncertainty" refers to the quality of the information, and "risk" refers to the probability of loss due to RBR.

Möykkynen and Pukkala (2009) and Möykkynen and Pukkala (2010) used simulations from the Rotstand model to investigate how RBR influenced the stands' optimal harvesting time and suggested reducing the rotation length to minimize the losses. Such results are useful for planning the management of the next forest generation. However, for a current rotation, they are only valid under the premise that we know the presence and severity of rot before making the harvest decision. However, without the costly procedure of examining samples taken from trees in the stand, the RBR infection and its severity can only be detected after trees have been cut.

However, it is possible to explicitly incorporate uncertainties into the decision-making by employing estimates of probabilities and methods that can account for risk (Eyvindson and Kangas 2018). Yousefpour et al. (2012) offer an extensive review of the most used models of risk analysis for forest management under climate change conditions. For instance, Brunette and Caurla (2016) used the Faustmann formula to address root rot risk-handling measures in the maritime pine forest, helping to determine the most economically relevant strategy. Reed (1984) adapted the Faustmann formula for infinite rotation to consider wildfire risk using a homogeneous Poisson distribution. Susaeta and Gong (2019) also investigated the risk of natural disasters by incorporating it into a reservation price model. Díaz-Yáñez et al. (2019) looked into how the risk of snow and wind damage can impact the harvesting ages in spruce forests in Norway. Bréda and Brunette (2019) investigated whether reducing the rotation length in a Douglas fir stand provided a better economic return under drought-induced risk. In all those cases, when the damage is instantaneous and complete, shortening the rotation length is recommended as the best management solution to minimize losses. Under varying disease conditions, Macpherson et al. (2016) have found that the value of timber from infected trees plays an important role in the decision of whether or not to shorten the rotation length of the forest. In our study, RBR damage develops slowly over time and results in partial losses. Under such conditions, no study has considered whether it pays off to harvest a forest stand earlier in case of RBR-related uncertainty, which is only revealed after the harvesting decision.

To fill this research gap, we consider as a case study a forest owner who should decide upon when to harvest forest stands while not knowing if and to which degree the stands are infected by RBR. By harvesting a stand on its economically optimal rotation age, we maximize the (expected) net present value (NPV) of the cash flow from the stand over the infinite time horizon. The concept of NPV over infinite rotations is also known as "land expectation value (LEV)", and it coincides with the approach first proposed by Faustmann (1849). We incorporate the uncertainties related to rot severity into the decision process by structuring the problem as a decision tree with several possible scenarios (states of nature). We investigate whether RBR-related uncertainty impacts the optimal rotation length and, if so, under what circumstances. We also calculate and ponder the relevance of the expected LEV loss in the current rotation when the decision-maker ignores the possibility of RBR infection. Regarding the infection/spread of the RBR over the stands, we rely on existing literature and build scenarios of different rot severities and their corresponding proportion of infected trees, to assess how this aspect of uncertainty may change decisions related to the harvesting age.

2 Material and methods

a. Study area and the stand data

We selected a forest area in the municipality of Våler (59° 30′ N, 10° 55′ E, 70–120 m a.s.l.) located in south-eastern Norway as a case study region. The main tree species are Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.), with some minor spots of Birch (*Betula pubescens* Ehrh.). The area has 100.2 ha of productive forest, an altitude of 70 m and an average temperature sum of 1406 d.d. Our database consisted of 43 stands that we assumed to be equal in the area (1 ha) for the sake of simplicity. The percentage of spruce in the stands varied from 8 to 100% (mean 59%, median 64%) and the initial ages from 35 to 94 years (mean 60, median 59).

To create the data on future stand development, we simulated forest growth for a fixed horizon of 46 years, starting from the stands' initial age. We used the forestry model GAYA (Hoen and Eid 1990; Hoen and Gobakken 1997) following the "mean tree" approach to obtaining diameter at breast height, height and the number of trees per hectare. We used GAYA 5-year time steps in calculations interpolated further to 1-year intervals. We calculated diameters at different heights by using the Kozak (1997) taper function calibrated to Norway (Pukkala et al. 2019) and used an optimal bucking algorithm implemented in R (R Core Team 2020) choosing the most profitable combination of log lengths, diameters and assortments.

b. Modelling the uncertainty

To assess the impact of the RBR-related uncertainty on the optimal rotation length of a stand, we compared the results obtained when ignoring the possibility of RBR versus considering the presence of RBR, even though its severity was not known. We represented this uncertainty by numerous possible rot scenarios representing levels of RBR severity within the stem and their corresponding proportion of infected trees. We used the scenarios to build a decision tree for the uncertainty analysis.

i. Structuring the decision tree

The decision tree analysis helps evaluate different management actions' outcomes in a systematic framework (Raiffa 1968). The idea behind decision trees is to divide the general uncertainty into a set of components and decisions that are less complex and easier to treat individually (McNamee and Celona 2007).

The decision tree we evaluated (Fig. 1) describes revenues obtained from harvesting a forest stand during 46 years, subject to 100 rot possibilities. According to Eyvindson and Kangas (2016), such a figure is large enough when only one uncertain variable is involved. The forest owner does not know which one of the rot possibilities prevails in the stand before it has been harvested.

Each scenario's outcome depends on the proportion of trees infected with RBR and the extent of the stem's decay.

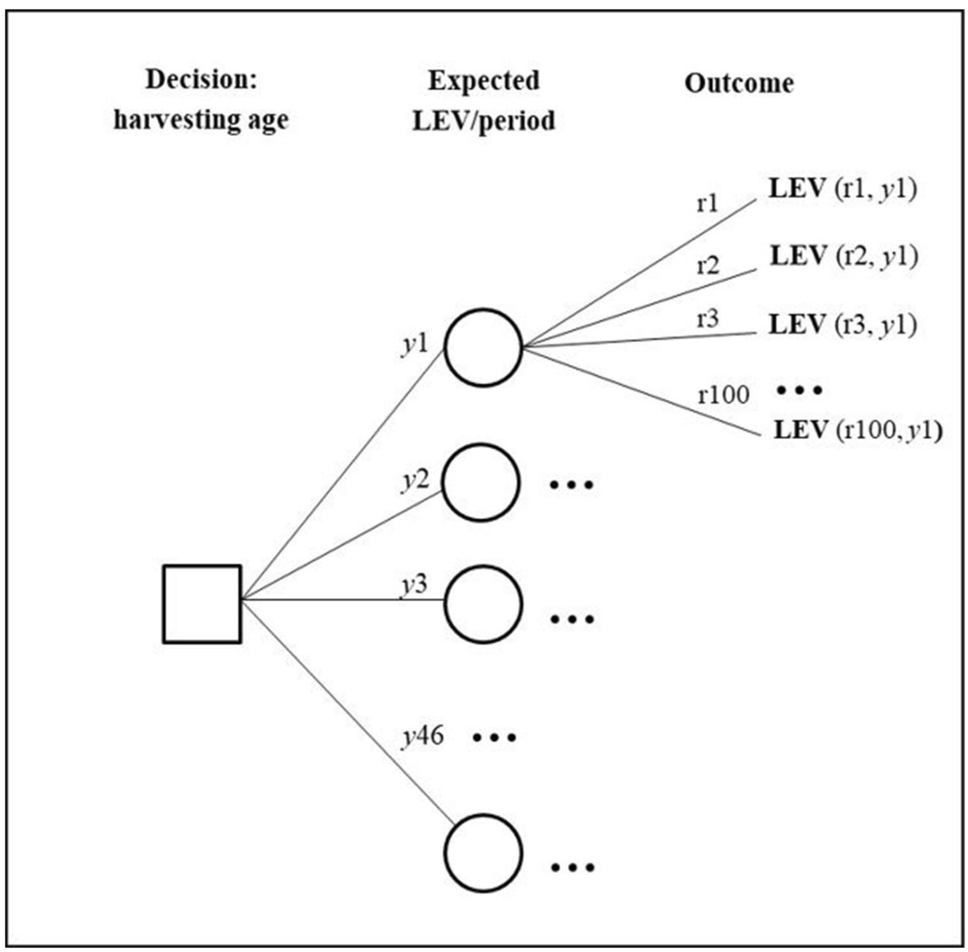

Fig. 1 Decision tree for a single stand. The starting point represents the choice of harvest time for a stand intending to maximize its expected LEV. We obtain the expected LEV by multiplying the LEV of each scenario (r1–r100) in a year by its probability of occurrence. The year with the largest expected LEV is the economically optimal rotation age

The proportion of infected trees is assumed to follow the model of Hylen and Granhus (2018). Although most parameters employed are common to all scenarios of a given stand (e.g. temperature sum of the growing season, altitude and vegetation type), the trees' diameter at breast height and age varies, thus generating different proportions of infected trees according to the age. The model predicts the probability of a tree to be infected, but since our data consist of the mean tree, we used it to obtain the proportion of the infected trees at the stand level.

The proportion of infected trees can be estimated as above, but the severity of the decay is uncertain, varying between 1 and 100% of the stump diameter. Huse et al. (1994) have collected information about frequencies of such occurrences in Norway from clear cuttings. The height of the decay column was calculated assuming the ratio "height of the decay column"/"width of the rot at the stump" to be 20.5:1 (Swedjemark and Stenlid 1993; Tamminen 1985). Furthermore, we assumed the decay column to follow the tree's shape. In the baseline simulations, we assumed the proportion of rot diameter of stump diameter to be constant over time from 1 to 100%.

The LEV in each rot scenario (r1–r100) for a given stand age and harvest time depends on the rot severity, the number of healthy and infected trees and eventually the economic value of the healthy and infected trees. To calculate the expected LEV at year *y* (Fig. 1), each rot scenario must have a probability assigned to it to represent the possibility that the result will occur. We used the relative frequency of RBR at different classes of rot diameters by Huse et al. (1994) as probabilities for the scenarios (Table 1). While it is possible that climate change may have affected the severity of the rot cases since the study was carried out, it is still the only information available for Norway. Frequencies were attributed to categories of rot diameter and we divided the probabilities by the number of scenarios within each category, obtaining the individual probabilities for each scenario considered in the decision tree.

ii. Defining the timber assortments

The RBR destroys the most valuable part of the tree, downgrading timber assortments to less valuable classes. The quantification of these losses is essential to determine the impact of the RBR on the economically optimal rotation age. Table 2 shows the dimensions considered to quantify the assortments. Any remaining parts at the stems not bucked into the described assortments were considered waste and left in the forest according to the operational forest management practice in Norway.

When the length of the decay column was smaller than 100 cm, the stem's base was bucked for the height of the decay and eliminated. The bucking algorithm simulated all possible combinations of assortments for the remaining stem, respecting the dimensions indicated in Table 2, choosing the one that provided the largest tree value. For the sawlog, we only considered timber without rot at any level. When rotten wood was present, the assortment of the log was assessed by the diameter of the rot. If the decay was smaller than 50% of the diameter at the stump base, it was considered rotten pulpwood. If it was larger than or equal to 50%, it was classified as energy wood.

iii. Costs and prices

To calculate each scenario's revenue, we considered 52 and 49 € m^{-3} for spruce and pine sawlogs, and 35, 33 and 31 € m^{-3} for spruce, pine and birch pulpwood, respectively. We assumed the price for energy wood as 15 € m^{-3}. Usually, the industry pays for rotten pulpwood the same price as healthy pulpwood if the decay does not exceed 50% of the log diameter. We employed the models of Dale et al. (1993) and Eid (1998) to estimate harvesting costs and Dale and Stamm (1994) and Eid (1998) for forwarding costs.

Table 1 Probabilities of occurrence of each scenario in the decision tree. Relative frequencies are from Huse et al. (1994)

Class of rot diameter in % of stump diameter	Relative frequency of *H. annosum* root rot	Number of scenarios within the class	Probability of each scenario within the class
0–10%	0.19	10	0.0190
11–25%	0.17	15	0.0113
26–50%	0.22	25	0.0088
51–80%	0.25	30	0.0083
81–100%	0.17	20	0.0085
Total	1.00	100	1.0000*

*Sum over all 100 scenarios

Table 2 Assortment definitions

Assortment	Decay level accepted (rot diameter in % of stump diameter)	Minimum diameter under bark (cm)	Maximum diameter under bark (cm)	Minimum log length (m)	Maximum log length (m)
Sawlog	0	13.5	60	3.4	5.8
Pulpwood	< 50%	4.0	70	3.0	5.5
Energy	≥ 50%	4.0	70	3.0	5.5

The baseline assumptions of this study consisted of an interest rate of 3% (which is the most typical value for Nordic countries, see Möykkynen et al. (2000)), full price for rotten pulpwood (35 € m^{-3}) and of a simplifying assumption that the proportion of rot diameter from stump diameter remains constant when the tree grows.

iv. Calculating the economically optimal rotation age

We calculated the NPV of the forest stand over an infinite time horizon, as given in Eq. (1). That gives the land expectation value in a discrete-time setting, where S_t refers to the stumpage value (€ ha^{-1}) at the age of stand t, I is silvicultural costs (€ ha^{-1}) and r is the interest rate. Stumpage value S_t corresponds to the revenues minus operational costs of harvesting a stand at age t.

$$LEV = \left(\left(S_t\frac{1}{(1+r)^t} - I\right)\left(\frac{(1+r)^t}{(1+r)^t - 1}\right)\right) \quad (1)$$

Subtracting silvicultural costs from the discounted stumpage value gives the NPV of one rotation for the bare land. To obtain the NPV of an infinite series of rotations (LEV), we multiplied the NPV of one rotation by the perpetuity factor, specified in the second part of the equation.

Using the LEVs of each scenario and its probability of occurrence, we calculated the expected LEV for each alternative harvest time. The harvest time t (stand age in years at the time of harvest) with the largest expected LEV is the economically optimal rotation length.

We also calculated the optimal rotation ages considering no rot infection. It was assumed to mimic a decision rule of a forest owner who ignores the rot risk. By comparing the harvest age of the simulations with and without rot, we found the impact of considering RBR-related uncertainty on the economically optimal rotation age of stands. We also calculated the expected loss caused by ignoring the possibility of RBR.

v. Sensitivity analysis

The following sensitivity analyses were done in addition to the baseline assumptions described above. (i) While a 3% interest rate was assumed as a default, results were also computed with the interest rate of 2%. (ii) Although the forest industries in Norway typically pay for rotten pulpwood the same price as for healthy pulpwood, we also calculated results assuming that rotten pulpwood was worth 50% of its original price, as in Honkaniemi et al. (2019). (iii) In addition to assuming the proportion of rot diameter of the stump diameter to remain constant over time, we calculated three cases of sensitivity analysis where the rot diameter grows faster than the stump diameter. In the baseline, the rot diameter is calculated as a fixed proportion of the stump base diameter over time. In the sensitivity analyses, however, the proportion of rot diameter from the stump base was defined to grow annually 1%, 2% or 5% so that they converge to the levels of 1–100% of the stump diameter at the rot-free optimal rotation age. Thus, each of the 100 rot possibilities was represented and the results were comparable to the baseline case.

3 Results

a. Results with two interest rates

By including RBR uncertainties in the calculations, the optimal rotation age differed from the simulation without rot in 14% of the stands (Fig. 2a) when simulating both 3 and 2% interest rates. Although this percentage coincides, we must point out the stands with age difference in each simulation were not the same. The average rotation length was reduced by 1.3 years for a 3% interest rate and 4.7 years for a 2% interest rate (Fig. 2b). We obtained the LEV loss by comparing the expected LEVs of the stand on its optimal rotation age without and with rot. In this case study, harvesting a forest that may be infected with RBR at its healthy rotation age generates an average LEV loss of 1.5 € ha^{-1} for a 3% interest rate. For a 2% interest rate, the average loss is 7.8 € ha^{-1}, reaching up to 26 € ha^{-1} in some stands (Fig. 2c).

b. Sensitivity to the pricing of rotten pulpwood

Assuming the regular price for rotten pulpwood (if decay is smaller than 50% of the diameter) reflects the current

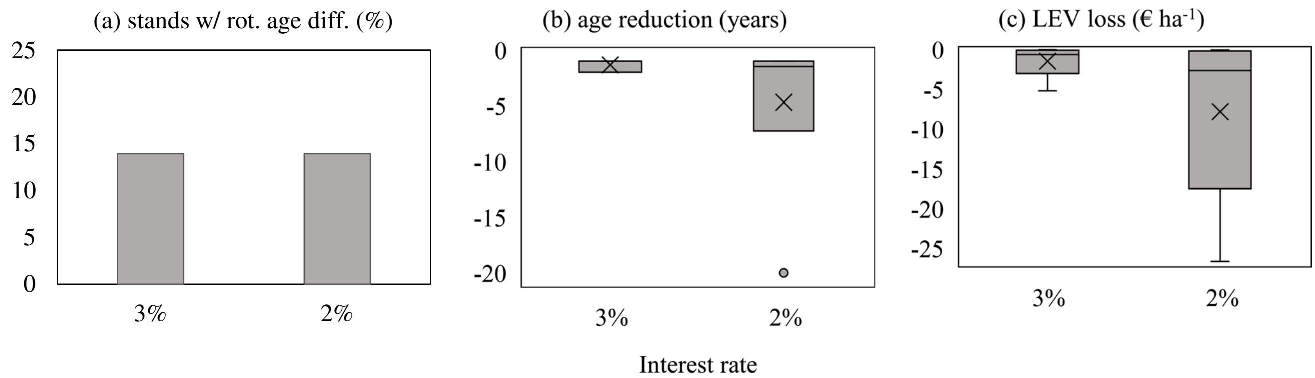

Fig. 2 Sensitivity of the analysis to the interest rate. We simulated 2% and 3% interest rates. **a** Percentage of stands with rotation age difference; **b** average age reduction (years) in stands with optimal rotation age difference; **c** average LEV loss (€ ha^{-1}) when harvesting the rotten stand on its healthy optimal rotation age

market in Norway. Yet, we investigated the results when maintaining the interest rate of 3% and changing the rotten pulpwood price from 35 to 18 € m^{-3}. The results, however, did not change much compared to the baseline. In both simulations, the inclusion of uncertainty reduced the optimal rotation age by 1.3 years in 14% of the stands evaluated (Fig. 3a and b). The only difference concerns the average LEV loss, which slightly increased from 1.5 € ha^{-1} (full price for rotten pulpwood) to 1.8 € ha^{-1} (half price for rotten pulpwood) (Fig. 3c).

c. Sensitivity to the rate of rot growth

For assessing the impact of rot growth rate on the variables of interest, we plotted the results against the baseline. The interest rate was kept at 3%. Whereas in the baseline the inclusion of uncertainty modified the optimal rotation age in 14% of the stands, this figure increased to 16, 21 and 23% in the simulations where rot grew 1, 2 and 5% faster, respectively (Fig. 4a). Following the same order, the average rotation length reduction, which was 1.3 years in the baseline, increased to 1.7, 2.9 and 2.7 years (Fig. 4b). Yet, we estimated the average LEV losses in 1.5 € ha^{-1} (baseline), 2.4 € ha^{-1} (rot growing 1% faster), 4.1 € ha^{-1} (rot growing 2% faster) and 5.0 € ha^{-1} (rot growing 5% faster) (Fig. 4c).

4 Discussion

In this paper, we analysed how the uncertainty related to the presence and intensity of RBR affects the economically optimal rotation age of forest stands. We investigated the effect of interest rate, pricing of rotten pulpwood and rate of rot growth. Although previous studies as Reed (1984) and Díaz-Yáñez et al. (2019) have found shortening the rotation age as the best option to maximize the LEV in forest stands at risk of catastrophes, our

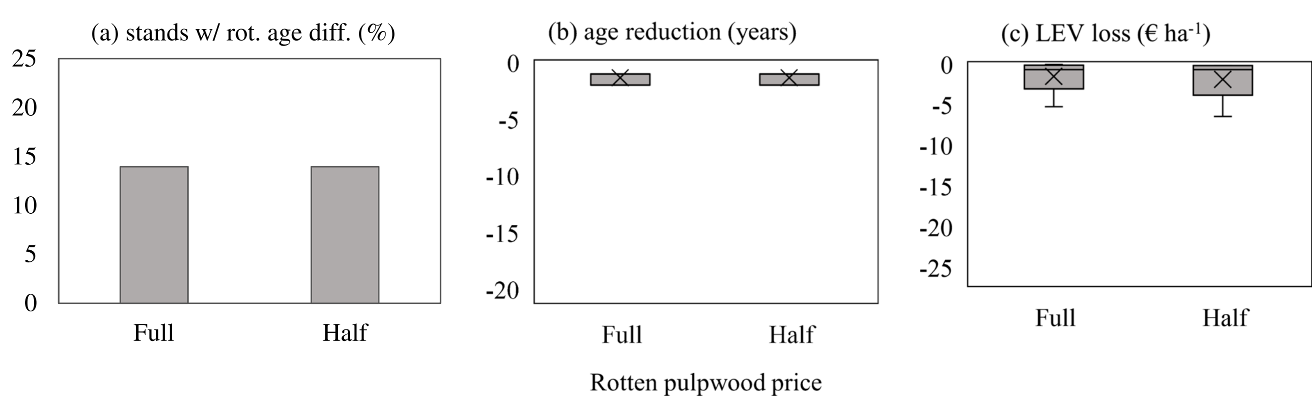

Fig. 3 Sensitivity of the analysis to the rotten pulpwood price. We simulated full and half prices for rotten pulpwood. **a** Percentage of stands with rotation age difference; **b** average age reduction (years) in stands with optimal rotation age difference; **c** average LEV loss (€ ha^{-1}) when harvesting the rotten stand on its healthy optimal rotation age

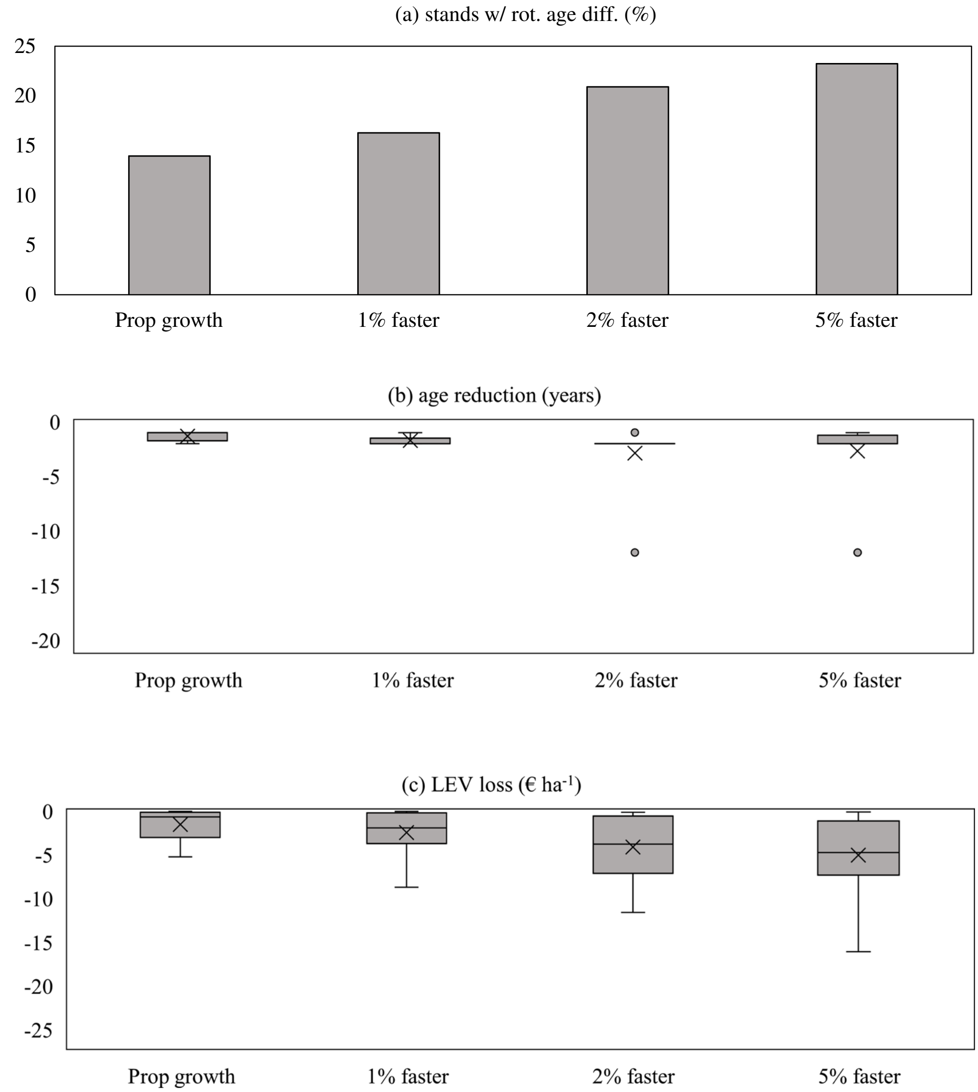

Fig. 4 Sensitivity of the analysis to a faster rot growth rate. We simulated rot growing 1, 2 and 5% faster than the tree. **a** Percentage of stands with rotation age difference; **b** average age reduction (years) in stands with optimal rotation age difference; **c** average LEV (€ ha^{-1}) loss when harvesting the rotten stand on its healthy optimal rotation age

results showed this may not always be the best solution when dealing with RBR.

Before discussing the sensitivity analysis in detail, we should highlight the context information that directly impacts the results and helps understanding in which situations it is worth considering the inclusion of RBR-related uncertainties in the harvest timing decision. As one might expect, stands with a large percentage of spruce are the target area. As the RBR does not affect pine and birch trees in Norway, the impact of the disease lies entirely on the spruce proportion. However, stands with a predominance of spruce

Table 3 Summary of results

Case	Stands with a rotation age difference	Average age reduction (years)			Expected LEV loss (€ ha^{-1})		
	Mean	Mean	Median	Std. Dev.	Mean	Median	Std. Dev.
3% interest rate	14%	1.3	1.0	0.5	1.5	0.7	2.0
2% interest rate	14%	4.7	1.5	7.6	7.8	2.7	10.7
50% pulpwood price	14%	1.3	1.0	0.5	1.9	0.7	2.5
Rot growth 1%	16%	1.7	2.0	0.5	2.5	1.9	3.0
Rot growth 2%	21%	2.9	2.0	3.4	4.1	3.8	4.0
Rot growth 5%	23%	2.7	2.0	3.3	5.0	4.7	4.8

will not always respond to the inclusion of uncertainty in the model. There are cases where the tree values with and without rot do not vary much, leaving the optimal rotation age of the stand unaffected.

Table 3 summarizes the results for all cases simulated. Under similar conditions to the baseline simulation (3% interest rate, full price for rotten pulpwood and rot growth proportional to the tree growth), our case study suggests that the decision-maker may not need to bother to shorten the rotation age of his/her forest. In a situation of uncertainty regarding the presence and severity of RBR, only a few stands would benefit from earlier harvesting. Still, the expected benefit would be negligible (1.5 € ha^{-1}).

Given the importance of the interest rate on the LEV calculation, we chose to simulate another somewhat widely used interest rate in Norway (2%) and compare it with our baseline. With both interest rates, the number of stands with optimal rotation age difference was coincidentally the same (14%). Some same stands responded to the possible presence of rot with both 2 and 3% interest rates, but more often the stands that changed their rotation were different ones in the two simulations. By analysing the results individually, we found the rotation length reduced by 1 or 2 years in most stands when using a 2% interest rate. However, there were two cases with a 3- and 20-year reduction which pulled the average age reduction down (4.7 years) and the expected LEV loss up (7.8 € ha^{-1}). In such stands, the LEV fluctuated slightly even in the healthy case during the age reduction period, making the optimal harvesting age very sensitive to the changes in assumptions. The greatest reductions in age came along with greater gains, although this figure was still low to be considered an incentive for changing the rotation. Regardless of that, we should note that although the reduction in rotation length is more pronounced when we use a lower interest rate, the number of stands affected remains small.

Assuming the regular price for rotten pulpwood (if decay is smaller than 50% of the diameter) reflects Norway's current market. However, we simulated a case assuming 50% of the original pulpwood price for rotten logs for the sake of comparison. There was barely any distinction when comparing the half-price simulation results to the baseline (which considers full price). Of course, the expected LEV in the simulation with half-price was lower than the one with full price. However, it does not mean there would be rotation age differences in more stands or a much larger LEV loss when compared to the baseline. This stability results from using an optimal bucking algorithm, which allows us to cut off up to 100 cm of rot column and rearrange the remaining assortments, maximizing the tree's value. As the average expected LEV of both simulations (full and half-price) are similar, it is predictable that the stands with rotation length differences would be the same. It seems that a lower price for rotten pulpwood should not have an additional effect on the optimal rotation length difference.

Previous research investigating the effect of catastrophic events on the optimal rotation age, such as Reed (1984) and Susaeta and Gong (2019), advocates for shortening the rotation length as the best management option to maximize the value of the stand. Also, Macpherson et al. (2016) show that under a risk of a pathogenic disease outbreak that would make the timber of trees affected by it worth nothing, shortening the rotation length is the optimal strategy for managing the land. Yet, they also found that when the trees affected have still some value after the outbreak, the optimal rotation length of these areas tends towards the disease-free optimal rotation length. This is also the case for RBR-infected areas, which align our results with those of Macpherson et al. (2016).

Finally, we simulated the case where the rot grows faster than the tree. As there is no reference for such faster growth, we assumed the hypothetical rates of 1, 2 and 5%. The results show that the larger the rot growth rate, the larger the number of stands with a rotation age difference. The average age reduction when considering the faster rot growth simulations is slightly larger than the baseline (rot growth proportional to tree growth). The LEV loss, which determines whether or not it is worth shortening the rotation age, increases in the simulation with faster rot growth, but its value remains modest in the context of forest management. Of all the sensitivities evaluated, faster rot growth indicated the way towards a possible reduction in the optimal rotation length. However, within the tested limits, this practice does not yet seem to make sense as a general rule.

A reduction in rotation length has been claimed as an efficient management strategy in areas affected by RBR (Möykkynen et al. 2000; Möykkynen and Pukkala 2009; Möykkynen and Pukkala 2010). Nevertheless, the choice of harvest time must be made without knowing to what extent the stand is affected by the RBR, as this information is difficult and expensive to obtain. In this case study, only a small proportion of the stands considered has responded to the inclusion of uncertainty in the model by reducing their optimal rotation age. Such age reduction was mostly limited to 1 or 2 years instead of the 6 years found in the literature for the same 3% interest rate (Möykkynen and Miina 2002; Möykkynen et al. 2000). A forest owner with an area and analysis conditions similar to ours would have a very modest financial benefit by harvesting his/her area earlier. The growth in volume and value of the trees not affected by the rot often overweighted the potential economic losses caused by rot in some of the trees in the stand. Furthermore, according to the previous studies on Norway (Huse et al. 1994; Möykkynen and Miina 2002), severe rot cases are somewhat as common as the cases of mild rot.

Reducing rotation length might bring other benefits not considered in this study, such as (i) reducing the time to which the damaged forest is exposed to further disturbances such as, for instance, windthrow and stem breakage (Seifert 2007); (ii) provide an earlier opportunity to change the tree species to more tolerant ones (Peri et al. 1990); (iii) decrease the damages the rot stored in the root system causes to the next tree generation (Wang et al. 2014) and (iv) avoid contamination in a broader spatial scale (Macpherson et al. 2016). On the other hand, it might also have a negative effect on carbon sequestration, biodiversity, etc., as mentioned by Bréda and Brunette (2019) and Kaipainen et al. (2004).

Some assumptions adopted may have restricted the variability of results, although they do not invalidate the study. For instance, by using a single tree approach rather than a mean tree, we would have allowed for greater flexibility and perhaps increased the variation affecting the proportion of infected trees and the assortments share. Introducing the variability of diameter is likely to increase the losses if we assume the proportion of infected stems remains fixed and the number of large trees increases. This effect would be even more visible by including the impact of the RBR infection on tree growth, as suggested by Pukkala et al. (2005). That remains to be studied in the future.

5 Conclusion

Deciding on the optimal rotation length of forest stands potentially infected with RBR requires integrating uncertainties related to the disease into the economic calculation. By using a decision tree, we obtained one common verdict over several RBR scenarios. We applied this technique, assuming different premises that might be feasible for a forest owner in Norway. Then, we evaluated the impact of the RBR-related uncertainty on the optimal harvesting time based on the expected NPV of the forest stands over infinite time.

Accounting for the possible but uncertain RBR infection reduced the economically optimal rotation length in 14–23% of the stands considered. The optimal age was reduced, on average, by 1.3–4.7 years. Although the simulations indicated the possibility of slightly reducing the rotation age in some stands, the expected gain obtained by harvesting a rotten stand earlier than its rot-free optimal rotation age was modest, leading us to question whether the practice is worthwhile. By reducing the rotten pulpwood price by 50%, there was barely any change in the final results compared to the baseline where we considered its full price. More stands showed differences in the optimal rotation age when accelerating rot growth relative to tree growth was assumed. Still, the expected economic gains were modest to motivate a change in management.

In most simulations, the possible but unknown RBR infection did not affect the optimal time of harvesting, and when it did, the small gains do not give a strong incentive for a change in management. The probability of severe infection is relatively small. Yet, the value growth of the trees combined compensates for the expected value reduction due to rot in some trees.

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Data availability The datasets generated/analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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