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Which trees should be removed in thinning treatments?



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Abstract

Background: In economically optimal management, trees that are removed in a thinning treatment should be selected on the basis of their value, relative value increment and the effect of removal on the growth of remaining trees. Large valuable trees with decreased value increment should be removed, especially when they overtop smaller trees.

Methods: This study optimized the tree selection rule in the thinning treatments of continuous cover management when the aim is to maximize the profitability of forest management. The weights of three criteria (stem value, relative value increment and effect of removal on the competition of remaining trees) were optimized together with thinning intervals.

Results and conclusions: The results confirmed the hypothesis that optimal thinning involves removing predominantly large trees. Increasing stumpage value, decreasing relative value increment, and increasing competitive influence increased the likelihood that removal is optimal decision. However, if the spatial distribution of trees is irregular, it is optimal to leave large trees in sparse places and remove somewhat smaller trees from dense places. However, the benefit of optimal thinning, as compared to diameter limit cutting is not usually large in pure one-species stands. On the contrary, removing the smallest trees from the stand may lead to significant (30–40 %) reductions in the net present value of harvest incomes.

Keywords: Continuous cover forestry, Tree selection, High thinning, Optimal management, Spatial distribution, Spatial growth model

Background

A tree is financially mature for cutting when its relative value increment falls below the guiding rate of interest (Davis and Johnson 1987; Knoke 2012). However, the value increment may improve in the future, due to e.g. changes in the proportions of timber assortments that can be obtained from the tree. Therefore, Duerr et al. (1956) advice to calculate the relative value increment for several coming time periods and classify the tree as financially mature if the highest projected rate of value increase is smaller than the guiding rate of interest.

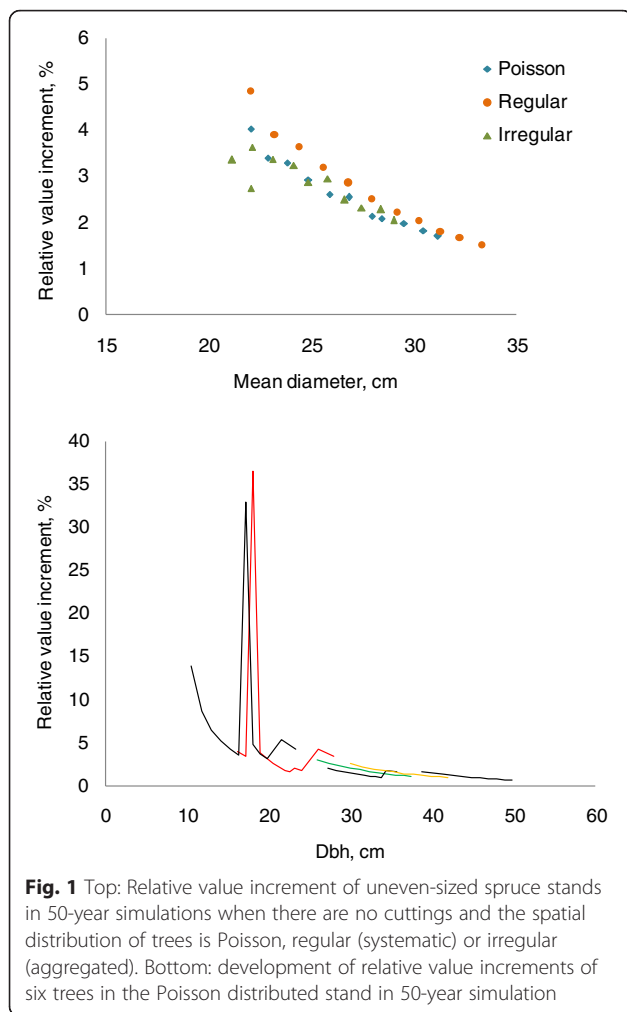
In Finland and many other countries the main timber assortments are pulpwood and saw log, of which saw log is more valuable. Figure 1 (bottom) shows that, in Finnish conditions, the consequence of unequal prices of different timber assortments is the existence of peaks in

relative value increment when the stem attains sufficient dimensions for pulpwood log, first saw log, second saw log etc. At later ages, when most of the volume is already saw log, the peaks gradually disappear and the relative value increment decreases monotonously with increasing tree age and size. If the tree has passed all the value jumps, it is enough to analyze the current value increment to judge whether the tree is financially mature for cutting. It is noteworthy, however, that different trees of the stand do not reach financial maturity at the same age or diameter (Fig. 1 bottom; Knoke 2012). This is because of genetic variation, spatial variation in site productivity, and differences in the competitive positions of the trees. The last factor can be taken into account in financial analysis if distance-dependent growth models are used to predict increment.

Figure 1 (top) shows that a regular spatial distribution of trees makes it possible to maintain sufficient value increments with larger average tree diameter as compared

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to more aggregated spatial arrangements. This means that, on the average, a tree reaches financial maturity at smaller diameter in irregular spatial distribution. However, some of the trees in an aggregated spatial tree distribution, growing in sparsely populated places or being surrounded by small trees, may grow better than a similar tree would grow in a regular stand, which postpones the financial maturity of these trees.

As Davis and Johnson (1987) pointed out, the effect of tree removal on the growth of remaining trees should also be taken into account when deciding when a tree should be harvested and which trees should be removed. Removing a large tree leads to improved value increment in smaller trees. This calls for cutting large trees earlier than their relative value increment suggests. The removal of a large tree may improve the productivity of several remaining trees and increase the relative value increment of the whole residual stand.

The capital invested in wood production consists of the value of the trees plus the value of bare land. If bare land has a positive value this means that a tree is financially

mature at higher relative value increment than indicated by the guiding rate of return. This is because the value increment must be compared to the opportunity cost of the tree and the piece of land occupied by the tree. Bare land value and the effect of tree removal on the growth of remaining trees both increase the rate of value increment at which cutting is optimal decision.

The above analysis suggests that it is optimal to remove the largest trees in a thinning treatment. However, unequal competitive status of trees, as well as unequal effect of tree removal on the growth of surrounding trees, makes the decision more complicated than for instance applying diameter limit cutting. A detailed analysis of optimal tree selection needs a distance dependent growth model, or at least the calculation of value increments and the effects of tree removal at individual tree level.

Although the overall principles that should determine tree selection in thinning have been understood and described already several decades ago (Duerr et al. 1956; Davis and Johnson 1987) few studies have actually optimized the selection of removed trees. An exception is the study of Pukkala and Miina (1998) who optimized a tree selection rule which was based on the effect of tree removal on the competitive positions of remaining trees. It was found that it was optimal to thin from above, i.e. remove large trees.

This study proposed a more straightforward approach to optimizing tree selection: the criteria of the cutting rule were the tree's stumpage value, its value increment, and the effect of removal on the growth of surrounding trees. It was assumed that increasing stumpage value, decreasing relative value increment and increasing competitive effect increase the likelihood of removal. Another hypothesis was that the optimal order of tree removal is less strongly correlated with tree diameter in irregular spatial distributions, as compared to regular tree arrangements. A third hypothesis was that, when net present value is maximized, it is optimal to remove trees at higher relative value increment than the discount rate that is used to calculate net present value.

Methods

Three different sample plots of Norway spruce (50 m by 50 m) with the same diameter distribution but different spatial distribution of trees were generated for the analyses. The first plot had a Poisson distribution of trees (henceforth referred to as Poisson stand). The x and y coordinates of trees were drawn from uniform distribution. The second stand was regular, and the third stand was very irregular (aggregated). Regular spatial distributions can be easily achieved by silvicultural treatments and the irregular distribution might be a result of removing all birches from a naturally emerged mixture of

birch and spruce. Spruces may be very irregularly distributed in such stands. The mean diameter of each initial stand was about 22 cm, stand basal area was 17 m²·ha⁻¹ and the number of trees per hectare was 1200. The stands were assumed to grow on mesic site in Central Finland.

The models of Pukkala et al. (2013) for diameter increment, tree survival and ingrowth were used in simulation. The models are based on about 60,000 diameter increment and survival observations in different stand types. The models can be used in both even-sized and uneven-sized stands. However, the models are not spatial. When the models were used in this study, the predictors which describe competition (stand basal area, G , and basal area in larger trees, BAL) were calculated from trees that were within 10 meters from the tree for which predictions were calculated. This is justified because most of the modelling data of Pukkala et al. (2013) were measured on plots with approximately 10-m radius. However, to make the growth simulator distance dependent, both G and BAL were calculated as the average G (m²·ha⁻¹) or BAL (m²·ha⁻¹) within 10 m, within 10/2 m (5 m), and within 10/3 m (3.33 m). As a result, the closest trees had a larger influence on G and BAL . This is in accordance with several studies, which show that the effect of neighbor trees on the growth of a subject tree decreases with increasing distance (see e.g. Miina and Pukkala 2000).

Mortality was simulated by comparing the tree's survival probability to random number distributed uniformly between 0 and 1. If the random number was larger than the survival probability, the tree was assigned as dead. Ingrowth (number of ingrowth trees) was predicted with the unmodified model of Pukkala et al. (2013) but spatial criterion was used to choose the places for ingrowth trees. Fifty candidate positions were generated for each ingrowth tree and the competition index proposed by Miina and Pukkala (2000; their Equation 6b) was calculated for each location. The tree was placed to that location which had the lowest completion index. The procedure mimics the observed dynamics of spruce stands (e.g. Eerikäinen et al. 2007) in which ingrowth trees appear in openings and places with little competition by larger trees.

The optimization problem consisted of selecting the thinning intervals and the weights of the three criteria of the following tree selection rule:

$$\begin{aligned} \text{RemovalScore} = & w_1 \text{Value} + w_2 \text{RelativeValueIncrement} \\ & + w_3 \text{BAEffect} \end{aligned} \quad (1)$$

where *Value* is the stumpage value of the stem, *RelativeValueIncrement* is the predicted 5-year value increment divided by the stumpage value of the stem, *BAEffect* is the total reduction in the BALs of neighbor trees in case

the tree is removed, and w_1 , w_2 and w_3 are optimized parameters which determine the effect of the three criteria on the order of tree removal. The BAL effect was calculated in the same way as BALs were calculated in growth prediction, i.e. by giving more weight to close neighborhood. A removed tree affected most within 3.33 m, somewhat less within 3.33–5 m, still less within 5–10 m and not at all beyond 10 meters.

The optimized parameters were thinning intervals and parameters w_1 , w_2 and w_3 of the tree selection rule. The problem formulations correspond to continuous cover management since planting was not an option when stand development was simulated. The remaining basal area was calculated with the following model, which is based on 20,583 optimized cuttings of 6,861 stands located in different parts of Finland. All optimizations meet the constraints of Finnish forestry legislation:

$$\begin{aligned} G_{\text{remain}} = & \exp(8.149 - 4.656D^{0.1} + 0.0221G_{\text{total}} \\ & + 0.211G_{\text{pine}}/G_{\text{total}} + 0.254G_{\text{spruce}}/G_{\text{total}} \\ & - 0.0327\sqrt{r} - 0.0333MT - 0.0992VT \\ & - 0.164CT) \end{aligned} \quad (2)$$

where G_{remain} is remaining basal area (m²·ha⁻¹), D is basal-area-weighted mean diameter of trees (cm), G_{total} is stand basal area before thinning (m²·ha⁻¹), G_{pine} is basal area of pine (m²·ha⁻¹), G_{spruce} is basal area of spruce (m²·ha⁻¹), r is discount rate (%), and MT , VT and CT are indicator variables for mesic, sub-xeric and xeric site, respectively.

When a thinning was simulated, trees were removed according to their removal score (Eq. 1) until the remaining basal area was equal to the value calculated with Eq. 2. In another set of optimizations, also the remaining basal was optimized. These optimizations may not always meet the current legal limits of Finland.

A 10-m wide buffer zone was generated around the plot when stand development was simulated (when computing the predictors of the models), and the buffer was removed after completing a simulation time step. The buffer was generated by assuming that the plot was surrounded by similar plots on all sides. Since the models that were used in growth simulation have five-year time step, stand development was simulated in 5-year steps.

Computation of the removal scores of trees involved the calculation of the stumpage value, 5-year value increment and BAL effect for every tree. To obtain the stumpage value, taper models (Laasasenaho 1982) were used to calculate assortment volumes, which were multiplied by their unit prices. The assortments were saw log (50 €·m⁻³, minimum top diameter 16 cm, minimum length 4 m), and pulpwood (15 €·m⁻³, minimum top diameter 9 cm,

minimum length 2 m). To calculate value increment, the diameter (dbh) and height of the tree were incremented by five-year growth, and assortment volumes corresponding to the incremented dimensions were calculated with the taper model.

The obtained stumpage values, value increments and BAL effects were used to calculate the removal scores for all trees, and the tree with the highest score was removed. Since a tree removal may affect the competitive influences, value increments and removal scores of remaining trees, the BAL effects and value increment predictions of all remaining trees were updated after every tree removal. This involved removing the buffer, generating the buffer again, and calculating the BAL effects and value increments again. Removing and adding the buffer after every tree removal was based on the assumption that the forest that surrounds the plot is thinned simultaneously with the plot.

Three next thinnings were optimized in the analyses of this study. The *NPV* of the ending growing stock (residual stand after the third thinning) was predicted with the model (see Pukkala 2015b). The model prediction, once discounted to the starting year of simulation, gives the *NPV* of all incomes and costs that are later than the last optimized cutting. It has been shown (Pukkala 2015a, 2015b) that using the model for estimate the *NPV* of distant cuttings has no major effect on the optimization results for the next cuttings, as compared to a higher number of optimized cuttings.

Since the simulation involves stochasticity in mortality and ingrowth, every simulation that was conducted during the optimization run was repeated 10 times and the mean *NPV* of the repeated simulations was used as the objective function (returned to the optimization algorithm). The direct search method of Hooke and Jeeves (1961) was used in optimization. Every optimization was repeated 5 times, each direct search starting from the best of 100 random combinations of optimized variables. The best solution (highest *NPV*) was taken as the optimal solution. *NPV* was calculated with 3 % discount rate.

Results and discussion

Remaining basal area not optimized

Optimizations in which the remaining basal area was not optimized suggested immediate thinning in all three stands, another thinning after 10 years, and a third thinning 10 years later (Table 1, boldface). However, there was some variation between repeated optimizations in the cutting intervals, especially in the irregular stand. Looking at the *NPVs* of the solutions suggests that those solutions that propose intervals other than 10 years may be sub-optimal, i.e., the algorithm has converged to local optimum.

The ranking of the three stands in terms of *NPV* was logical. The regular stand produced the highest *NPV* whereas the highly irregular stand produced clearly smaller economic benefit than the other stands (Table 1).

Table 1 Net present values and optimal values of decision variables for Poisson, regular and irregular stand in 5 repeated optimizations when the remaining basal area of thinning was calculated with a model (Eq. 2)

<i>NPV</i> (€·ha ⁻¹)	Years to 1st thinning	Years to 2nd thinning	Years to 3rd thinning	<i>w</i> ₁ (stem value)	<i>w</i> ₂ (value increment)	<i>w</i> ₃ (BAL effect)
Poisson stand						
9133	0	10	10	0.37	-0.25	0.38
9121	0	10	15	0.24	-0.47	0.29
9127	0	10	10	0.48	-0.50	0.02
9032	0	15	15	0.43	-0.27	0.29
9105	0	10	10	0.29	-0.05	0.66
Regular stand						
9319	0	10	10	0.35	-0.31	0.34
9237	0	10	20	0.49	-0.27	0.24
9304	0	15	10	0.78	-0.04	0.18
9289	0	15	15	0.46	-0.29	0.26
9313	0	10	15	0.30	-0.13	0.57
Irregular stand						
8247	0	10	10	0.42	-0.13	0.45
6852	0	25	45	0.46	-0.27	0.26
8266	0	10	10	0.32	-0.43	0.25
7511	0	30	10	0.38	-0.30	0.32
8238	0	10	35	0.50	0.01	0.52

Optimization result with the highest *NPV* is indicated with boldface

The signs of the parameters of the removal score function were logical: high stem value and high BAL effect (high reduction in the competition of remaining trees) increased the score, and high relative value increment decreased it. Valuable trees with low value increment and strong competitive effect on other trees were the first ones to leave. As a result, thinnings from above were conducted, as can be seen from the maps of Fig. 2.

A closer inspection of the diameters of the removed and remaining trees (Fig. 3) revealed that the thinnings of the regular stand resembled diameter limit cutting. There were only one or two diameter classes which included both remaining and removed trees. In the first thinning of the Poisson forest, there were 4 diameter classes (8 cm diameter range) having both remaining and removed trees. This range was 12 cm in the irregular stand. Large trees were left in sparse places and rather small trees were removed from dense places.

The diagrams of Fig. 4 (bottom right) show that, in the regular stand, the order of removal followed decreasing breast height diameter fairly closely. The selection score correlated closely with both dbh and relative value increment, suggesting that either of these variables alone could

be used as the harvesting criterion in a regular stand. In the other stands, the order of removal did not follow decreasing dbh equally closely. In both Poisson and regular stands, most trees removed in the first thinning were larger than 25 cm.

The situation was different on the irregular stand, in which several removed trees were smaller than 25 cm. To have a sufficient remaining basal area, some large trees were left to continue growing (Figs. 2 and 3). In the irregular stand, the removal score did not correlate strongly with dbh or relative value increment. In this stand, the BAL effect of tree removal varied much more than in the other stands (Fig. 4 bottom left) and had a stronger influence on the removal score than in the other stands. This cannot be concluded from the weights of BAL effect in Table 1 since the effect of the criterion depends on both the weight and the range of variation in the criterion variable in a particular stand and thinning. As a conclusion, when thinning an irregular stand, more importance should be given to the reduction of competition due to tree removal.

Table 1 shows that repeated optimizations result in different weights of the criteria of the removal score,



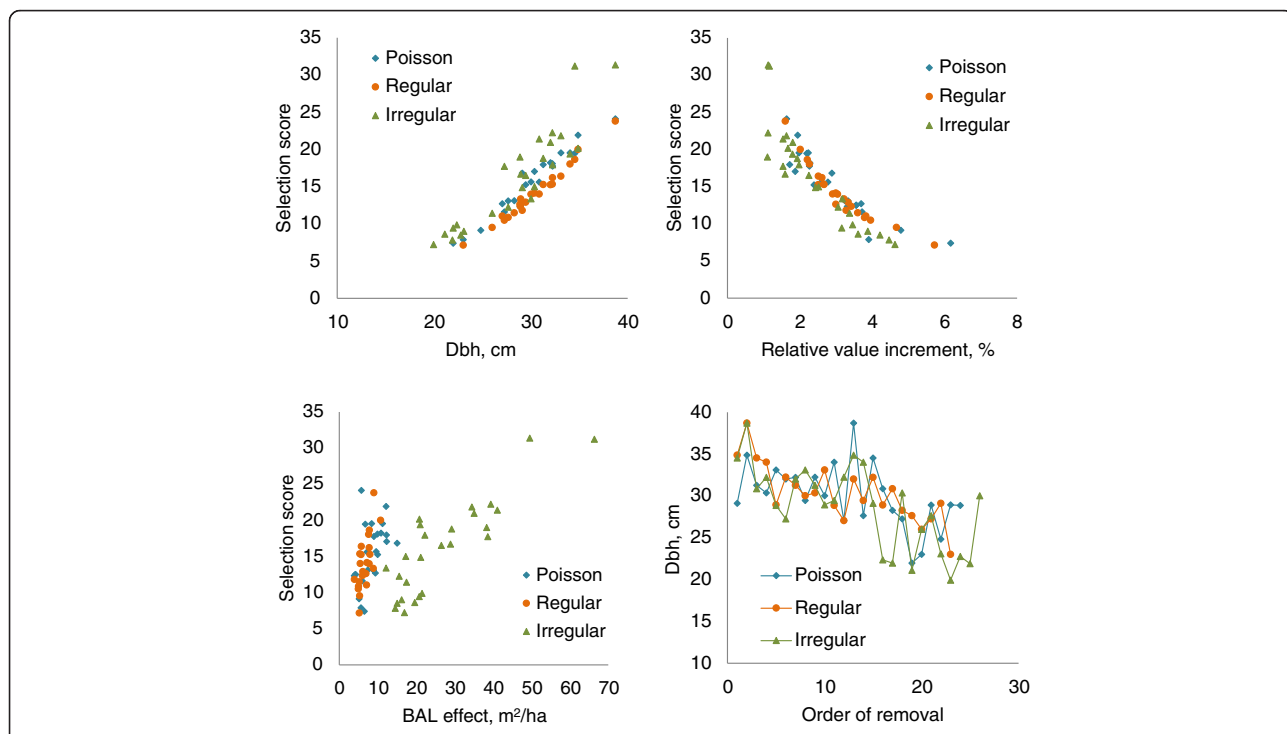


Fig. 4 Correlation of the tree selection score of the first thinning with dbh, relative value increment and BAL effect (reduced competition of other trees if the tree is removed). The bottom-right diagram shows the dbh of the removed trees as a function of the order of removal (trees on the left are removed first and trees on the right are the last trees removed)

Another simulation was done by applying the optimal weights of the thinning rules (boldface rows in Table 1) of the three different stands to the first thinning of the Poisson stand (Fig. 6). The results show again that nearly the same trees were removed from the Poisson forest

when applying the optimal tree selection rule of regular, irregular or Poisson stand. This result implies that the same tree selection rule could be used in all spatial distributions, which may sound counterintuitive in the light of the diagrams of Fig. 4. However, even though the

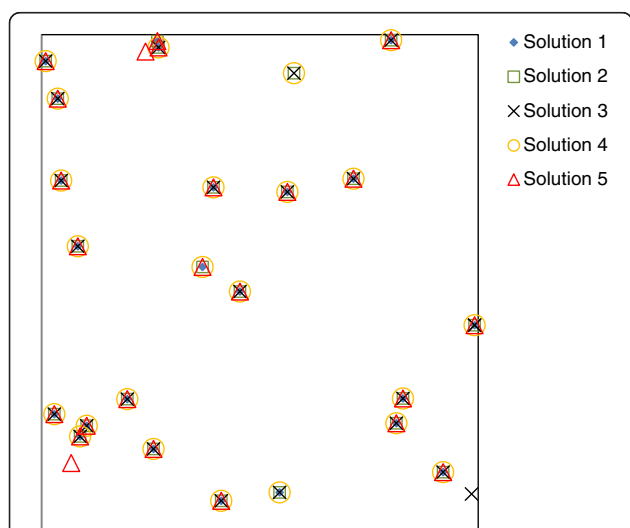


Fig. 5 Location of trees removed in the first thinning of the Poisson stand when tree selection is based on five different solutions of the optimization problem. When the symbols of different solutions coincide, the same tree is removed in all solutions

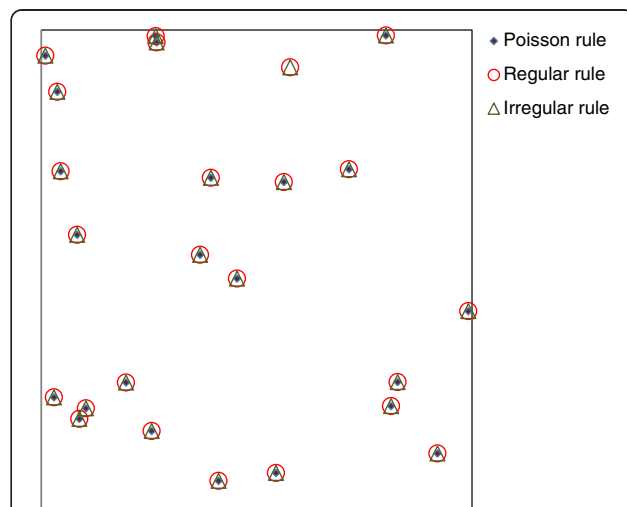


Fig. 6 Location of trees removed in the first thinning of the Poisson stand when tree selection is based on the optimal tree selection rule obtained for Poisson stand, regular stand and irregular stand. When the symbols of different rules coincide, the same tree is removed with all rules

weight of e.g. BAL effect would be the same in all stands, the influence of BAL effect on tree removal would be stronger in the irregular stand, due to greater variation of BAL effect in this stand.

Remaining basal area optimized

When the remaining basal area was optimized together with the thinning intervals and tree selection rule, the NPV of the optimal schedule increased by 4–5 % as compared to optimizations in which remaining basal area was calculated with Eq. 2 (Tables 1 and 2). The remaining basal areas were now 6.5–8.9 m²·ha⁻¹ whereas they were 10–11 m²·ha⁻¹ when calculated with the model. The thinning intervals became longer in the Poisson and regular stands. It can be concluded that the requirement for a certain minimum residual basal area decreased the profitability of forest management in the three analyzed stands.

As a consequence of stronger thinnings, more ingrowth appeared in the stands, especially in the Poisson and regular stands, as compared to previous optimizations (Fig. 7). The thinning was extended to smaller diameters (Fig. 8), and the diameter range that had both remaining and removed trees, became narrower. This means that when remaining basal area was not restricted, optimal thinning resembled more diameter limit cutting, also in the aggregated spatial distribution.

The optimality of diameter limit cutting was further inspected by removing the trees according to dbh, starting from the largest tree ('High thinning' in Fig. 9). For comparison, simulations were also conducted so that the smallest trees were removed in the thinning treatments ('Low thinning' in Fig. 9). The results show that systematic diameter limit cutting was not much worse than optimal tree selection. Thinning from below would be a clearly inferior management approach.

Effect of discount rate

The previous optimizations used 3 % discount rate. When remaining basal area was optimized in the Poisson stand (together with thinning intervals and tree selection rule), lower discount rate (1 %) led to clearly longer thinning intervals, higher pre-thinning basal areas, larger mean tree diameters, and slightly higher post-thinning basal areas and mean diameters, compared to 3 % discount rate

(Fig. 10). Increased discount rate (5 %) resulted in 10-year thinning interval, lower remaining basal area and smaller mean tree size of the residual stand. When the discount rate was 1 %, the largest trees of the stand were 35 cm in dbh when the thinning was conducted. With 5 % discount rate the thinning was conducted when the largest trees reached 25 cm breast height diameter.

The effect of discount rate was the most clear in growing stock value (Fig. 10, bottom left). When the discount rate was 1 %, the stumpage value of the growing stock was 8000 €·ha⁻¹ at the second thinning and 13 000 €·ha⁻¹ at the third thinning. With 5 % discount rate the pre-thinning growing stock value was only about 2200 €·ha⁻¹.

When NPV was maximized with 1 % discount rate, it was optimal to thin the stand when its relative value increment was 2–3 %. With 3 % discount rate the stand was thinned at 4.5–6 % value increment, and at with 5 % discount rate at 8 % value increment. When the discount rate was 3 %, in the first thinning of the Poisson stand about half of the removed trees had a relative value increment of about 2 % and the rest had 3–6 % rate of value increment (Fig. 11, top). However, the first thinning, which was immediately, was most probably later than its optimal timing would have been. In later thinnings, 50 % of removed trees were removed at about 4 % rate of value increment and the rest were removed at higher, up to 7 % value increment.

In the second thinning of the Poisson stand, trees were removed at 2–7 % value increments when discount rate was 1 %, at 3–7 % increments when discount rate was 3 % and at 5–14 % value increments when discount rate was 5 % (Fig. 11, bottom). This is in line with the hypothesis of the study, according to which it is optimal to remove a tree at higher relative value increment than the guiding rate of interest. This is because of the opportunity cost of bare land and the fact that tree removal improves the relative value increment of remaining trees.

Conclusions

The results suggest that it is nearly optimal to select the trees that are removed in a thinning treatment on the basis of breast height diameter, starting from the largest tree. However, in irregular spatial distributions, the competition faced by the tree and the effect of removal on

Table 2 Net present values and optimal values of decision variables for Poisson, regular and irregular stand when the remaining basal area (G) was optimized together with thinning intervals and tree selection rule

Stand	NPV (€·ha ⁻¹)	1st thinning		2nd thinning		3rd thinning		w_1 (stem value)	w_2 (value increment)	w_3 (BAL effect)
		Years	G	Years	G	Years	G			
Poisson	9477	0	6.9	15	8.9	20	7.4	0.33	-0.45	0.22
Regular	9680	0	6.5	15	7.7	20	7.6	0.68	-0.25	0.07
Irregular	8671	0	6.9	10	8.6	10	6.8	0.83	-0.09	0.08

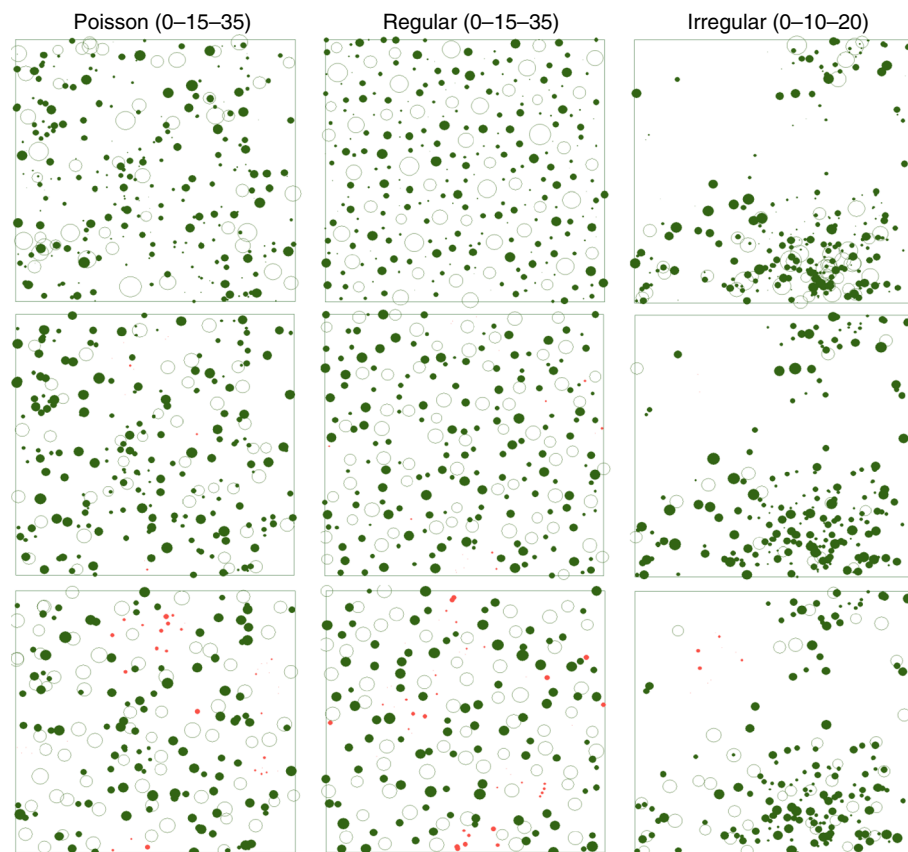
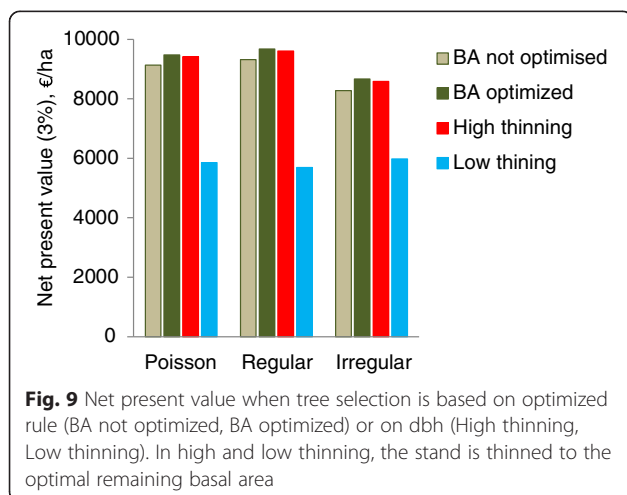
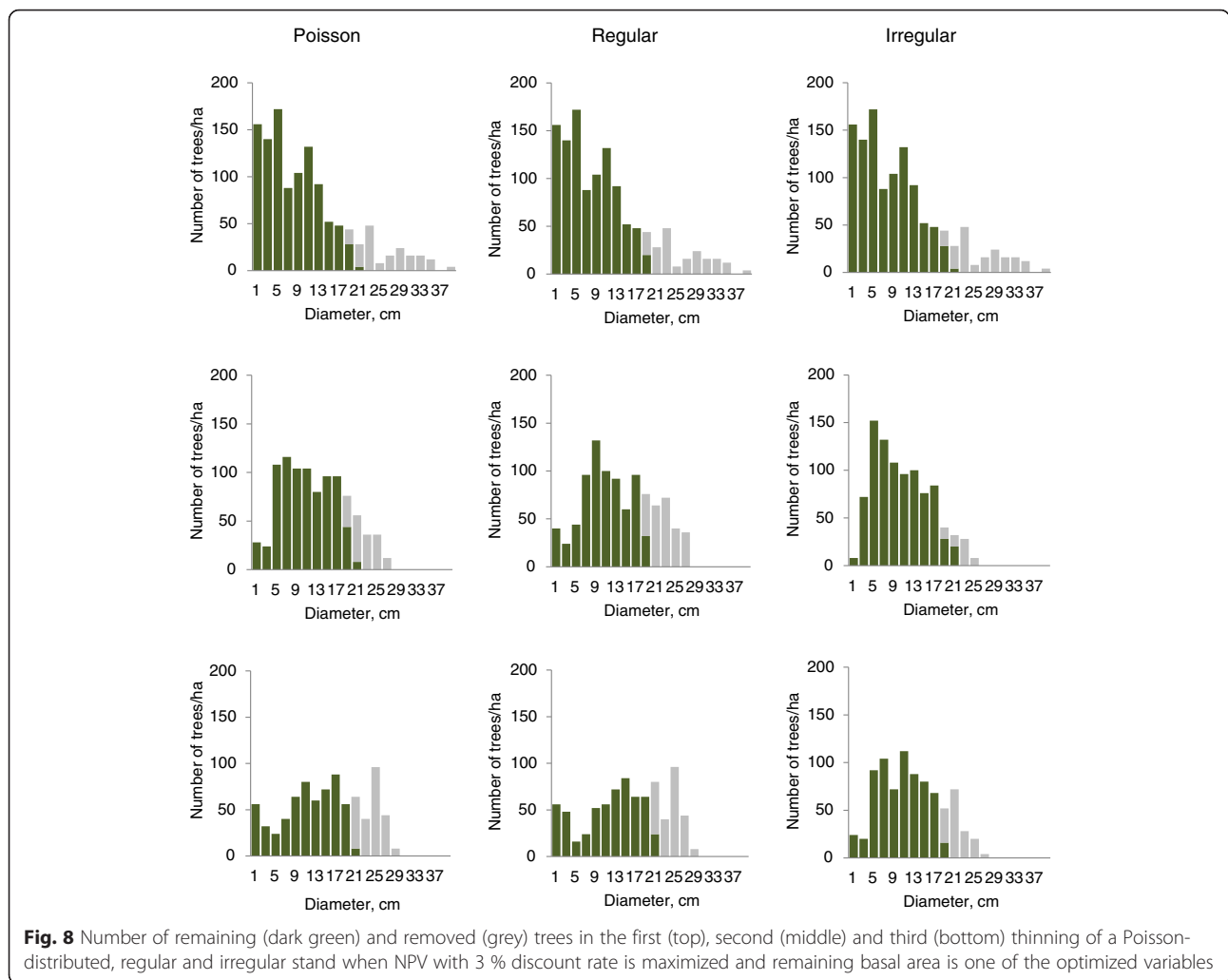


Fig. 7 Remaining (filled circles) and removed (open circles) trees in the first (top), second (middle) and third (bottom) thinning of a Poisson-distributed, regular and irregular stand when the remaining basal area is optimized. Ingrowth trees are shown with lighter tone (red). Thinning years are given in parentheses

the growth of surrounding trees should also be taken into account. The degree of irregularity of the irregular stand of this study was so high that such stands are rarely encountered in managed forests. Therefore, diameter limit cutting seems to be a sufficient approach in most stands. However, there are other types of irregularity, which are more common. For example, the stand may have sub-areas of predominantly large trees while other sub-areas are occupied by smaller trees. In this case, diameter limit cutting leads to openings and unutilized growing space. Since decreased competition increases the dbh of financial maturity, it would most probably be better to leave some large trees to continue growing. This means that a tree selection rule that incorporates several criteria is more likely to work better (than dbh alone) in a wide range of stand structures. In mixed stands, relative value increment or a more complicated tree selection rule is certainly better than using only dbh to select the removed trees (Knoke 2012). This is because of differences in the inherent growth rates, assortments dimensions, and assortment prices of different species.

Although there are very few previous studies on optimal tree selection, several recent results on pre- and post-cutting diameter distributions in economically optimal uneven-aged management support the conclusion that optimal cutting resembles diameter-limit cutting (Tahvonen et al. 2010; Tahvonen 2011; Pukkala et al. 2014; Pukkala 2015a, 2015b). The American studies conducted during the 1980s lead to similar conclusions (Haight 1985, 1987; Haight and Getz 1987). Also long-term silvicultural trials support the conclusion that diameter limit cutting is more profitable than single-tree selection. For example, in the Vessari experiment located in Central Finland, the net present value (calculated with 3 % discount rate) of diameter limit cutting was 13750 €·ha⁻¹ whereas it was only 10250 €·ha⁻¹ in single tree selection during a 40-year monitoring period. In the nearby Honkamäki experiment the NPV of diameter limit cutting was 10500 €·ha⁻¹ and the NPV of single tree selection was 7800 €/ha (Pukkala et al. 2012).

The optimizations of this study were done for continuous cover management. However, the same principles of analyzing the financial maturity of trees also apply to



even-aged management. Several studies have shown that the optimal thinning of a certain stand would be rather similar in even-aged management and continuous cover forestry (e.g. Pukkala 2015b). In the study of Pukkala et al. (2014), which optimized the cuttings of 200 different stands representing different stand structures without the limitation to pursue either even-aged management or continuous cover forestry, 97–99 % of thinnings were high thinnings similar to those that were found optimal in this study. However, some studies (Valsta 1992; Hyytiäinen et al. 2005; Pukkala 2015b) have found that, in even-aged management when a forced clear-felling belongs to the management schedule, it is sometimes optimal to remove trees from both ends of the diameter distribution.

Tree quality, health and vigor are additional characteristics which should affect tree selection. However, these criteria are difficult to include in simulation and optimization studies. As suggested already Möller (1922), trees whose vigor is decreased should be removed

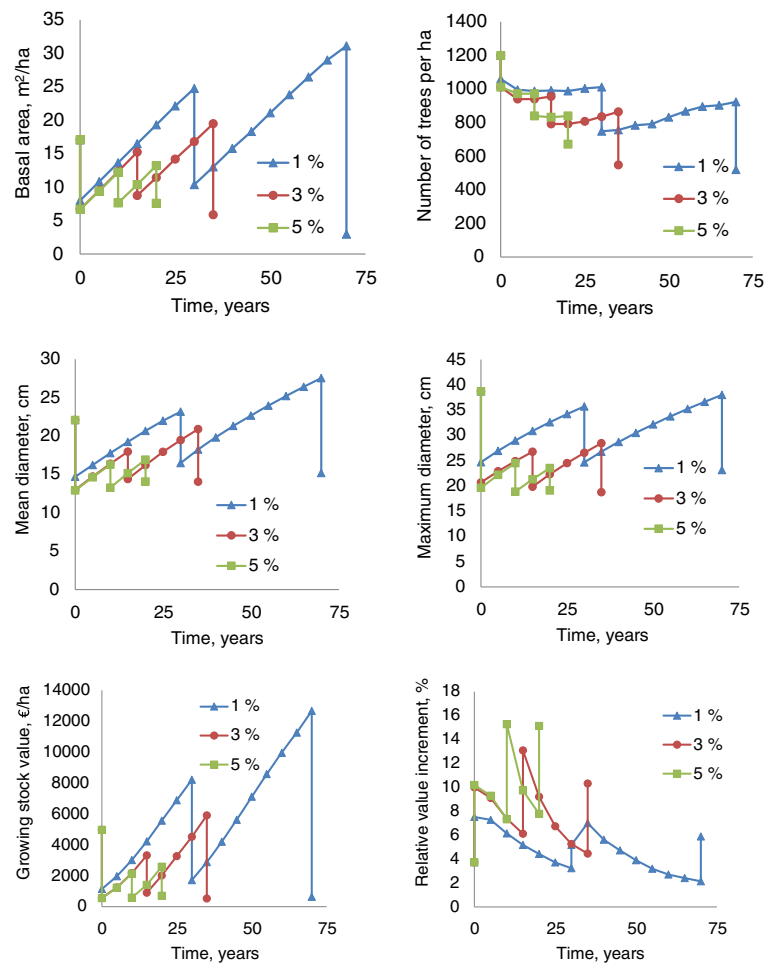


Fig. 10 Development of stand basal area, number of trees per hectare, mean diameter, maximum diameter, growing stock value and relative value increment in the optimal management schedule of the Poisson forest when NPV is maximized with 1, 3 and 5 % discount rate

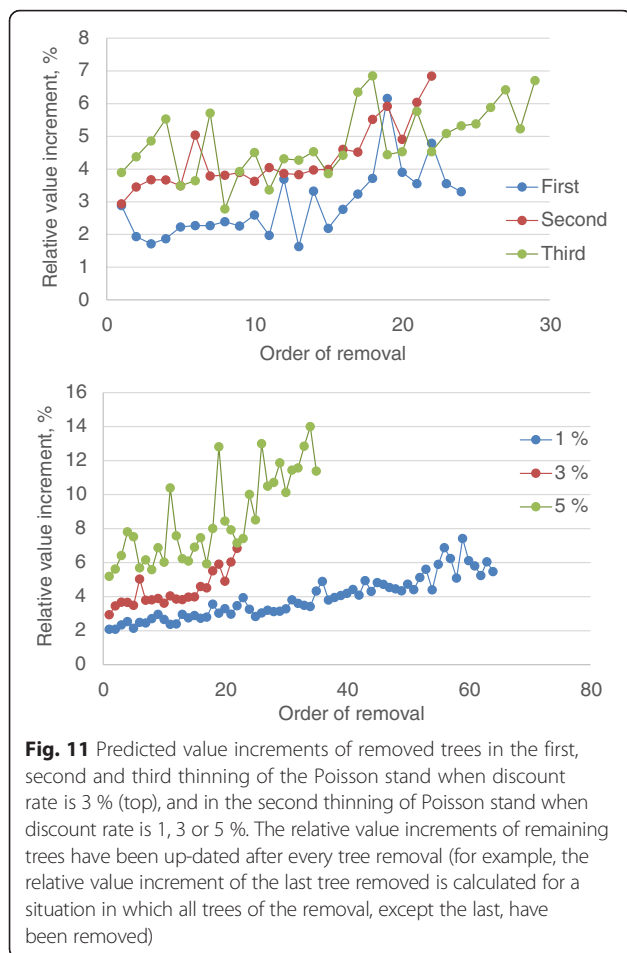
in thinnings. If low-quality trees overtop smaller and better-quality individuals, they should also be removed, as commonly done in forestry practice. If the quality of all trees is low (or equal), the criteria proposed in this study can be used.

The optimal tree selection rules that were developed in this study, all lead to thinning from above. The comparison of Fig. 9 also shows that thinning from below may not be economically justified. This can also be concluded from earlier literature that discusses financial maturity (Duerr et al. 1956; Davis and Johnson 1987; Knoke 2012). Also several optimization studies show that high thinning is in most cases more profitable than low thinning (e.g., Haight and Monserud 1990; Valsta 1992; Tahvonen et al. 2013). In fact, it is hard to find economic arguments which would justify the use of low thinning.

The study used a non-spatial model in spatial simulation. It was justified by the fact that the area of computing the competition variables (G and BAL) corresponds to the

area of the sample plots in the modelling data of Pukkala et al. (2013). However, there is one difference: in the modelling data, G and BAL were computed within 300- m^2 plots (around 10 m radius) for all trees of the plot, not only for trees near plot center. These values of G and BAL may not describe the competition that edge trees face in the best possible way because trees outside the plot also create competition. This may be called as “sampling error” in the calculation of G and BAL for the edge trees in individual-tree growth modelling. Sampling error results in weaker relationship (underestimated influence) between growth and G or BAL in the growth model. In the current study, this underestimation was counteracted by the distance-dependent computation of G and BAL , which increased their variation. As a result, the predictions may in fact be better than when calculating G and BAL in the same way as they were computed in the data preparation step of growth modelling.

The simulations of this study included stochasticity in mortality and ingrowth. Therefore, every simulation



was repeated 10 times and the mean *NPV* of the 10 simulations was used as the value of the management schedule. Ten simulations is a small number in stochastic simulation. However, few trees die in managed forests, and dead trees are usually small. Ingrowth begins to affect harvest removals and stand value gradually, its effect being minimal during the first decades although ingrowth is critically important for the long-term sustainability of continuous cover forestry. Therefore, it can be concluded that the two sources of stochasticity (mortality and ingrowth) did not have any significant effect on the results of this study.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

TP conducted the analyses. EL and OL participated in the writing of the manuscript. All authors have read and approved the final manuscript.

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