



Improved guidelines for any-aged forestry

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Abstract Any-aged forest management (AAF) is a means to reduce clear-felling without compromising profitability or timber production. The concept of AAF is to choose between clear-felling or thinning one harvest at a time based on what is better at that time in terms of the management objectives for the forest. No permanent choice is made between rotation forest management (RFM) and continuous cover forestry (CCF). Optimized AAF is never less profitable than RFM or CCF because all cutting types of both RFM and CCF are also allowed in AAF. This study developed a new set of guidelines for managing boreal forest stands under AAF when the forest landowner maximizes economic profitability. The first part of the guidelines indicates whether the stand should be cut or left to grow. This advice is based on stand basal area, mean tree diameter, minimum allowable post-thinning basal area, site productivity, and discount rate. If the optimal decision is harvesting, the second instruction determines whether the harvest should be clear-felling or thinning. In the case of thinning, the remaining two steps determine the optimal harvest rate in different diameter classes. The guidelines were developed using two different modeling approaches, regression analysis, and optimization, and applied to two Finnish forest holdings, one representing

the southern boreal zone and the other the northern parts of the boreal zone. The results show that AAF improves profitability compared to current Finnish management instructions for RFM. The use of clear-felling also decreased the lower the minimum acceptable post-thinning basal area of the stand.

Keywords Management optimization · Silvicultural system · Differential evolution

Introduction

Silvicultural systems have traditionally been classified into even- and uneven-aged management (Hanewinkel 2002; Hynynen et al. 2019). Continuous cover forestry (CCF) has also been frequently discussed in recent literature (Knoke 2012; Pukkala 2016; Mason et al. 2021). CCF corresponds to the German Dauerwald concept, the essential elements of which are to avoid clear-felling, rely on natural regeneration, and remove mature, diseased, and low-quality trees (Troup 1927). Maintaining tree cover and providing a continuous supply of ecosystem services are important characteristics of CCF (Möller 1922). Typical of CCF management is that mixed stands are also favored (Möller 1922). In contrast to uneven-aged management, continuous maintenance of uneven-aged stand structure or fixed harvest removals at regular intervals is not required in CCF. According to Heliwell (1997), the goals of CCF are to avoid clear-felling, abandon the concepts of age-class and rotation, and not allow regeneration to drive the system. From an economic point of view, an important feature of CCF is to aim for a high economic return with low capital (Heliwell 1997), which translates into good economic profitability.

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Considering the features of CCF, i.e., uninterrupted supply of ecosystem services, high tree species diversity, and economic profitability, it is obvious that CCF corresponds to the management objectives of most multiple-use forests. Several recent studies indicate that CCF outperforms or is competitive with even-aged rotation management in economic profitability (Tahvonen 2009; Pukkala 2016; Peura et al. 2018), carbon sequestration (Pukkala 2014; Assmuth and Tahvonen 2018; Peura et al. 2018; Díaz-Yáñez et al. 2020; Parkatti and Tahvonen 2021), and biodiversity indicators (Peura et al. 2018; Díaz-Yáñez et al. 2020; Eyvindson et al. 2020).

However, if clear-felling is ruled out, forested landscapes may no longer correspond to structures that natural dynamics would produce. Berglund and Kuuluvainen (2020) concluded that, without human intervention, non-stand replacing disturbance dynamics would dominate in Fennoscandian forests but there would be a certain percentage of stands, perhaps 20%, which would illustrate stand replacing dynamics. This means, for example, that for ecological sustainability, it would be good to have a portion of the forest under even-aged management, although the majority (around 80%) should be managed for more complex stand structures. If forest management and other activities reduce the damage caused by storms and wildfires, it may be justified to use clear-felling to mimic these hazards (Schall et al. 2017). Refraining from all clearcuttings also may not be economically optimal (Tahvonen and Rämö 2016). There might be situations where natural regeneration is scarce, and the existing tree cover is no longer productive. Natural regeneration via seed or shelter trees is not always feasible due, for instance, to a high risk of wind damage or poor germination conditions.

Therefore, it has been suggested that CCF alone may not be the best silvicultural system for multipurpose forests but mixtures of different management systems (Peura et al. 2016; Pohjanmies et al. 2017; Eyvindson et al. 2018), or the so-called free-style or any-aged management (AAF) should be used instead (Haight and Monserud 1990a, b; Boncina 2011; Pukkala 2018). The concept of AAF is that all types of cuttings are allowed all the time, and no permanent choice is made between CCF and even-aged management. The likely outcome of optimized AAF is the frequent use of thinning from above and infrequent use of clear-felling and planting (Díaz-Yáñez et al. 2020). Clear-felling might be used in cases of insufficient natural regeneration or excessively high opportunity cost of the growing stock. However, a single clear-felling does not indicate a permanent switch from CCF to even-aged management.

There are already optimizations-based instructions for employing AAF in Finnish forests (Pukkala 2018). These guidelines have been used in a few studies that have compared alternative silvicultural systems. These studies suggest

that AAF outperforms both CCF and RFM in economic profitability (Pukkala 2021), and is competitive with CCF in biodiversity maintenance, wood production, and carbon sequestration (Díaz-Yáñez et al. 2020; Pukkala 2021). The results are logical since AAF is less constrained than CCF and RFM, and all the management options available in CCF and RFM can also be used in AAF.

AAF guidelines for Finnish forests (Pukkala 2018) consist of three rules, of which the first shows the probability that immediate cutting is the optimal decision. This probability depends on the discount rate, stand basal area, mean diameter of trees, site fertility, and temperature sum, which describes the total accumulated temperature of the growing season. If the first rule recommends harvesting, the second determines whether the harvest should be a final felling or a thinning. An additional factor, (compared to the first rule), affecting the choice between thinning or clear-felling, is the basal area of pulpwood-size trees. If it is $5 \text{ m}^2 \text{ ha}^{-1}$ or more, it is almost certain that thinning from above is the optimal cutting method. If a thinning treatment is selected, the third rule indicates the harvest percentages for different diameter classes.

Although the AAF guidelines described above are recent, there are a number of reasons to update them. New growth models, suitable for simulating and optimizing AAF, have been published (Pukkala et al. 2021). It may be expected that these models describe the growth and dynamics of current Finnish forests better than those on which previous AAF guidelines are based. Another reason is that a new way to derive management instructions has been suggested (Jin et al. 2019). The current guidelines consist of four models that have been fitted separately to a high number of stand-level optimization results using regression analysis. This is a two-step procedure consisting of separate optimization and model fitting steps. The idea of this new method is to develop a complete set of rules in one step by optimizing the parameters of all sub-models of the management guideline. The management of a set of stands is simulated with all parameter combinations that are inspected during the optimization run, seeking values that would result in the best objective function value when calculated over all stands used in the analysis. The study by Jin et al. (2019) shows that the two approaches, fitting regression models to stand-level optimization results, or optimizing the instruction directly, do not necessarily result in similar management guidelines.

A third reason for updating the AAF guidelines is that the current instructions omit a factor that has a significant influence on the choice between a final felling or thinning. This is the lowest allowed post-thinning stand density, usually measured by basal area. Previous studies show that thinning from above replaces clear-felling the more the lower the minimum allowed post-thinning basal area (Pukkala et al. 2014). In Finland, the lowest post-thinning basal

area is dictated by forestry legislation (Anonymous 2013). However, there may be case-specific reasons to set the limit higher. The most important of these is the risk of wind damage, which may increase considerably if a dense stand is thinned to a low basal area (Zubuzarreta-Gerendiain et al. 2012; Pukkala et al. 2016). The risk of wind damage varies for different regions, forest holdings and stands, and depends on wind patterns of the region, soil type, and shelter that an adjacent stand or the terrain provide. The lowest acceptable stand density may also depend on management objectives. For example, if the landowners aim for increased forest carbon stocks, they might avoid low stocking levels.

The objective of the current study was to develop new management guidelines for AAF in such a way that the lowest allowed post-cutting basal area is considered, in addition to the discount rate, site productivity, and growing stock characteristics. The optimization-based one-step approach for developing the guidelines is tested as an alternative to the two-step regression-based approach. The analyses utilize the most recent growth, survival, and ingrowth models published in Finland (Pukkala et al. 2021).

Materials and methods

Overview of the steps

Three harvests of a sample of Finnish forest stands were optimized in such a way that all types of cuttings were allowed (partial cutting from below, partial cutting from above, clear-felling). This optimization produced data for modeling the cutting decision, i.e., the dependence of the optimal moment and the optimal way to do the cutting, based on site fertility, discount rate, growing stock characteristics, and other relevant variables.

If a cutting schedule tested during optimization included clear-felling, the simulation was terminated, and the bare land value was added to the net income of clear-felling. The bare land value describes the net present value (NPV) of all future incomes and costs. To facilitate this approach, new models for bare land value were developed in this study.

If the management schedule tested did not include clear-felling, the NPV of the residual growing stock was calculated and added to the NPV of the simulated cuttings. The predicted NPV of the final growing stock describes the NPV of all cuttings carried out after the third optimized cutting. For this, new models were developed for predicting the value of the final growing stock.

The optimization results for the individual stands were used to develop models for optimal stand management. The growing stock variables were saved at 5-year intervals. If the optimal schedule involved a harvest at the end of the 5-year period, the type of the cutting (final vs. partial) was

also recorded. In the case of partial cutting, information about the thinning intensity in different diameter classes was written on the output file.

The discount rate used in the optimization of a particular stand was random and uniformly distributed between 1 and 5%. The timber price was also random. The roadside prices of conifer sawlogs and pulpwood correlated as shown in Fig. 1. Birch had the same pulpwood price as conifers, but the sawlog price of birch was 10 € m⁻³ lower. The lowest allowed post-thinning basal area was also randomized.

Stand-level optimization produced a dataset that was used to develop the following models:

- The probability that cutting the stand now is the optimal decision
- In the case of cutting, the probability that partial cutting (thinning) is the optimal decision
- In the case of partial cutting, the optimal thinning intensities of different diameter classes

These models were fitted in regression analysis. Because the discount rate, timber price, and lowest allowed post-cutting basal area varied, it was possible to model the effect of these variables on the optimal management.

The same models were then fitted simultaneously using an approach where the parameters of the rules (the models listed above) are the optimized decision variables (Jin et al. 2019). In this approach, the management of each stand of the dataset was simulated with all parameter combinations that were tested during the optimization run. Those parameters that gave the highest NPV, when calculated over all stands of the dataset, were the optimal ones.

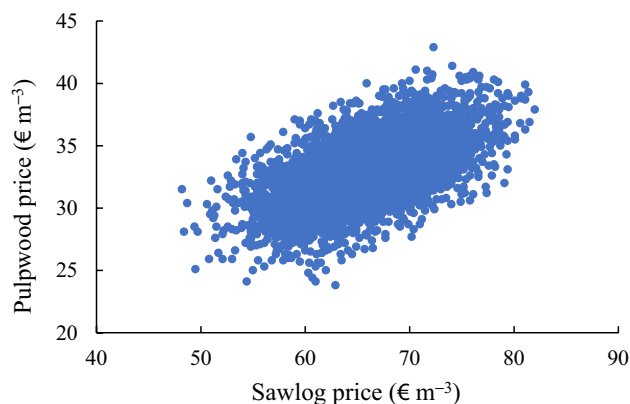


Fig. 1 Assumed distribution of the roadside price of sawlogs and pulpwood. The random prices used for a particular stand were drawn from this distribution

Models used simulation

The stand dynamics (diameter increment, survival, and ingrowth) were simulated using the models of Pukkala et al. (2021) and tree heights with the model of Pukkala et al. (2009). The assortment volumes of harvested trees were calculated with the taper models of Laasasenaho (1982). The net income of cutting was calculated by subtracting the harvesting and forwarding costs from the roadside value of harvested timber (sawlogs and pulpwood). The costs were based on the time consumption functions of Rummukainen et al. (1995), and the hourly costs of 95 € for the harvester and 65 € for the forwarder. The time consumption functions considered the fact that the cost per harvested cubic meter depends on the size of harvested trees, volume harvested per hectare, and type of the cutting, thinning being more expensive than clear-felling.

Modeling the value of bare and forested land

To produce data for modeling bare land value, even-aged management schedules were optimized for several forest types, discount rates, temperature sum regions, and timber prices, starting with bare land. The first treatment was always site preparation and the next was planting spruce on mesic and better sites, or sowing pine on other sites. The total cost of site preparation and planting was 1100 € ha⁻¹, and the total cost of site preparation and sowing was 700 € ha⁻¹. It was assumed that the management schedule included two tending treatments (years 3 and 10, costs of 350 € ha⁻¹ and 450 € ha⁻¹) on mesic and better sites, and one tending treatment (year 6, 450 € ha⁻¹) on sub-xeric and poorer sites. The used discount rates were 1, 2, 3, and 4% and the site types were herb-rich (representing herb-rich and better sites), mesic, sub-xeric, xeric, and heath. All optimizations were repeated for four temperature sum regions: 1400, 1200, 1000, and 800 degree days (d.d). In addition, the optimizations used five timber price levels: normal level, and normal level ± 10 and ± 20%. The “normal” roadside price was 60 € m⁻³ for conifer sawlogs and 30 € m⁻³ for pulpwood. These combinations resulted in 2000 optimizations and were used to model bare land value (net present value) as a function of temperature sum, site fertility, timber price, and discount rate. The models for bare land value are reported in Appendix 1 (Table S1).

Modeling the value of forested land

For developing models for forested land, the next three cuttings were optimized for a large number of stands. When the cutting schedule did not include clear-felling, the NPV after the third optimized cutting was predicted with an existing model (Ruotsalainen et al. 2021). All costs and incomes,

as well as the value of the residual forest, were discounted to the starting year of the simulation. These optimizations produced data for fitting updated models for the value of forested land. The optimizations were repeated using the updated models for the value of the residual forest, and the models were fitted again using the new optimization results. This was repeated twice more and was found to be sufficient for stabilized results. The models for the value of forested land are reported in Appendix 2 (Table S2).

The stands used in the optimizations were drawn from the Metsaan.fi database using stratified random sampling. The samples were drawn separately for three latitudinal ranges (60–62.99, 63–65.99, > 66 degrees) and in each range, the sample was drawn separately for four site fertility categories: (1) herb-rich and better, (2) mesic, (3) sub-xeric, and (4) xeric and poorer. The sampling ratio was adjusted in such a way that each sub-sample included approximately 150 stands. The total number of stands in the 12 strata (three latitude ranges, four site classes) was 1651, slightly less than the target (3 × 4 × 150 = 1800) since the sub-sample was not always exactly 150 and stands without any trees were not used.

Producing data for management instructions

Once the models for bare land and forested land were completed, optimizations for the 1651 stands were repeated using random timber prices, discount rate, and minimum post-cutting basal area. The variables optimized for each cutting were:

- Number of years since the beginning of the simulation (1st cut) or previous cut (2nd and 3rd cutting)
- Two parameters of the thinning intensity curve (Eq. 1)

Therefore, the total number of optimized variables was nine. If a partial cut led to a post-thinning basal area lower than the minimum allowed, the schedule was penalized with the consequence that such a schedule was never selected as the optimum. However, if the cutting was clear-felling, there was no penalty. Final felling interrupted the simulation since the NPV of subsequent cuttings was based on the predicted bare land value. A cutting was interpreted to be a clear-felling if the post-cutting basal area was less than 0.25 times the minimum allowed post-thinning basal area.

The thinning intensity in different diameter classes was described with the following:

$$p_{\text{remove}}(d) = \frac{1}{1 + \exp [a_1 (a_2 - d)]} \quad (1)$$

where $p_{\text{remove}}(d)$ is the proportion of trees removed when the diameter is d cm and a_1 and a_2 are parameters optimized

for each cutting. Parameter a_2 shows the dbh at which the thinning intensity is 50%. Parameter a_1 shows the type thinning. If $a_1 > 0$, the thinning is from above, i.e., the thinning intensity increases towards larger trees. If $a_1 = 0$, the thinning intensity is the same for all diameter classes, and $a_1 < 0$ indicates thinning from below. In this study, parameter a_2 is referred to as the thinning intensity parameter and a_1 as the thinning type of parameter.

The results of the optimal management schedules were used to fit the following set of models which serve as management guidelines for any-aged forest management:

$$p_{\text{cut}} = f(G, G_{\text{min}}, D, R, TS, P_{\text{sl}}, P_{\text{pw}}, \text{Site}) \tag{2}$$

$$p_{\text{thin}} = f(G, G_{\text{min}}, G_{\text{pulp}}, D, R, TS, P_{\text{sl}}, P_{\text{pw}}, \text{Site}) \tag{3}$$

$$a_1 = f(G, G_{\text{min}}, G_{\text{pulp}}, D, R, TS, P_{\text{sl}}, P_{\text{pw}}, \text{Site}) \tag{4}$$

$$a_2 = f(G, G_{\text{min}}, G_{\text{pulp}}, D, R, TS, P_{\text{sl}}, P_{\text{pw}}, \text{Site}) \tag{5}$$

where p_{cut} is the probability of cutting (probability that cutting the stand now is the optimal decision), p_{thin} is the probability that the optimal type of cutting is thinning, and a_1 and a_2 are the parameters of the thinning intensity curve (Eq. 1). G is the stand basal area, G_{min} is the minimum allowed post-thinning basal area, G_{pulp} is the basal area of pulpwood-sized stems (dbh 8–18 cm), D is the basal-area-weighted mean diameter, R is the discount rate, TS is the temperature sum, Site is the site fertility class, P_{sl} is the roadside price of sawlogs, and P_{pw} is the roadside price of pulpwood. The predictors and model forms were adopted from a previous study (Pukkala 2018) but the model forms were not forced to be the same. G_{min} (the lowest allowed post-thinning basal area) was a new variable not tested by Pukkala (2018). The analyses indicated that timber price was not a significant predictor of models 2–5 and it was therefore not used in the final model versions.

The model for the probability that cutting is the optimal decision (Eq. 2) was based on all stands of the optimal management schedules. The simulation software saved the stand states at five-year intervals. However, cases where it was optimal to cut the stand immediately were not used in modeling. There may sometimes be situations where the optimal time of cutting has already passed, i.e., the cutting is late in economic terms. The use of these cases would have resulted in biased models for the optimal timing of cutting.

All stands in which there was a cutting prescription (also cases where the cutting was prescribed immediately) were then used to fit a model for the probability that the optimal cutting type was thinning. Finally, all stands in which a

thinning treatment was prescribed were used of fit models for the parameters of the thinning intensity curve (Eq. 1).

Optimization-based one-step procedure for developing management guidelines

The parameters of management rules (Eqs. 2, 3, 4 and 5) were also found using an alternative, optimization-based method suggested by Jin et al. (2019). In this optimization, the management schedules of the stands were not optimized separately. Instead, the parameters of Eqs. 2, 3, 4 and 5 were optimized. The development and management of each stand (of the set of 1651 stands) were simulated with each combination of the parameters tested during the optimization run. The parameter combination that gave the highest NPV was assumed to be optimal.

Timber price, discount rate, and the lowest allowed post-thinning basal area were also randomized in this optimization. However, drawing new random values for the stands at the beginning of each new simulation would lead to a situation where repeated runs with the same values might result in different net present values, which makes it difficult for the optimization algorithm to find the optimal parameter values. Therefore, the random discount rate, timber prices, and minimum post-cutting basal area were assigned to the stands at the beginning of the optimization, and the same values were used in all simulations during the optimization run.

Optimization aimed at maximizing the NPV of all 1651 stands. However, as the discount rate was not the same for all stands, calculating the average or total NPV of the stands would be equal to giving more weight to low discount rates because the NPV increases with decreasing discount rates. Therefore, the NPVs based on different discount rates were weighted as follows. First, a model was fitted between discount (R , %) rate and NPV (€ ha^{-1}), based on the separate optimizations of the management schedules of the stands:

$$\text{NPV} = 31869R^{-1.49} \tag{6}$$

The weight of the NPV of stand j (w_j) was then calculated as follows:

$$w_j = (1/31869R_j^{-1.49}) / 0.0000172 \tag{7}$$

where R_j is the discount rate used for stand j . The formula scales the weights so that their mean is equal to one when the discount rate is uniformly distributed between 1 and 5%.

The parameter optimization maximized the following function:

$$\text{argmax}_{\theta} = \sum_{j=1}^{1651} w_j \text{NPV}(\theta)_j \tag{8}$$

where w_j is the weight and NPV_j the NPV of stand j and θ the set of parameters of the cutting rules (Eqs. 2, 3, 4 and 5). Weight w_j was a function of the discount rate (Eq. 7), which was different for different stands.

Optimization methods

In the regression-based approach, stand-level optimization problems were solved with the direct search method of Hooke and Jeeves (1961). The number of optimized variables was nine (three cutting intervals plus two additional parameters per cutting) or less than nine if one of the cuttings was clear-felling. Hooke and Jeeves (1961) employed two search modes, exploratory and pattern search. In exploratory search, increased and decreased values of the decision variables are tested one at a time. All changes that improve the objective function (OF) value (NPV in this study) are accepted, and all non-improving changes are rejected. If an increased value does not improve the OF value, a decreased value is tested.

After inspecting all decision variables, the algorithm switches to the pattern search, where the values of several decision variables are modified simultaneously. The magnitudes of the changes (search direction) depend on the changes made in the preceding exploratory search. The algorithm then starts a new exploratory search using 50% smaller change steps than in the previous exploratory search. Repeating the search modes, with a gradual reduction in the magnitude of the changes, the algorithm gradually finds the optimal or near-optimal values of decision variables.

The performance of the method of Hooke and Jeeves (1961) may decrease if the number of optimized variables is high (Jin et al. 2018). In the optimization-based approach for deriving the management guidelines for AAF, the number of simultaneously optimized variables was 32 (parameters of Eqs. 2, 3, 4 and 5). Therefore, another method, differential evolution (Storn and Price 1997) was used. Differential evolution operates with several solution vectors or several sets of optimized variables. A recommended number of solution vectors is about 10 times the number of optimized variables. In this study, differential evolution was implemented with 300 solution vectors. Each solution vector was initialized with uniform random numbers. The ranges of the random numbers were based on the regression-based parameter values of the AAF instructions. The minimum value of the range was equal to 0.5 times the value of the parameter in the regression model, and the maximum value was obtained by doubling the regression coefficient.

After initialization, all solution vectors were used to simulate the development of each of the 1651 stands. The simulations yielded the OF value (Eq. 8) for each vector. The population of solution vectors was then modified for several iterations aimed at improving the quality of the solutions. A so-called noise vector was generated for each solution vector as follows:

$$y_i = a_i + \lambda (b_i - c_i) \quad (9)$$

where y_i is the value of parameter i in the noise vector, a_i , b_i and c_i values of the same parameter in three other, randomly selected solution vectors, and λ is a parameter (0.5 used in this study). Each element of the solution vector was then replaced by the noise vector value with a certain probability (0.5 used in this study). However, in one, randomly selected solution vector, all elements were replaced by the noise vector value. If the modified solution vector was better than the non-modified one, the modified vector replaced the non-modified one.

The above process was repeated for all solution vectors for several iterations. The solution of the differential evolution algorithm was the best solution vector at the end of the last iteration.

Results

Probability of cutting

The model for the probability that cutting the stand was the optimal decision is:

$$P_{\text{cut}} = \frac{1}{1 + \exp[-(X)]} \quad (10)$$

where

$$X = 8.2960 - 0.6058 \ln G_{\min} + 1.694 \ln D \ln G - 0.2667 \sqrt{D} \sqrt{G} + 0.001001 TS \ln R - 2.619 \ln TS - 0.6846H - 0.1784M - 0.07603 \quad (11)$$

in the regression-based approach and

$$X = 8.8088 - 0.7444nG_{\min} + 1.9687 \ln D \ln G - 0.2500 \sqrt{D} \sqrt{G} + 0.001371 TS \ln R - 2.8760 \ln TS - 0.6799H - 0.24474M - 0.0585S \quad (12)$$

in the optimization-based approach. The explanatory variables were minimum allowed post-thinning basal area (G_{\min} , $\text{m}^2 \text{ha}^{-1}$), basal-area-weighted mean diameter (D , cm), stand basal area (G , $\text{m}^2 \text{ha}^{-1}$), temperature sum (TS , d.d.), discount rate (R , %) and three indicator variables for site fertility categories: H = herb-rich or better, M = mesic, S = sub-xeric. All indicator variables are zero if the site fertility class is xeric or poorer.

The models show that the probability of cutting increases with increasing basal area and mean diameter (Fig. 2). The probability that cutting is the optimal decision also increases with an increasing discount rate. Increasing temperature sums and improving site fertility decrease the probability

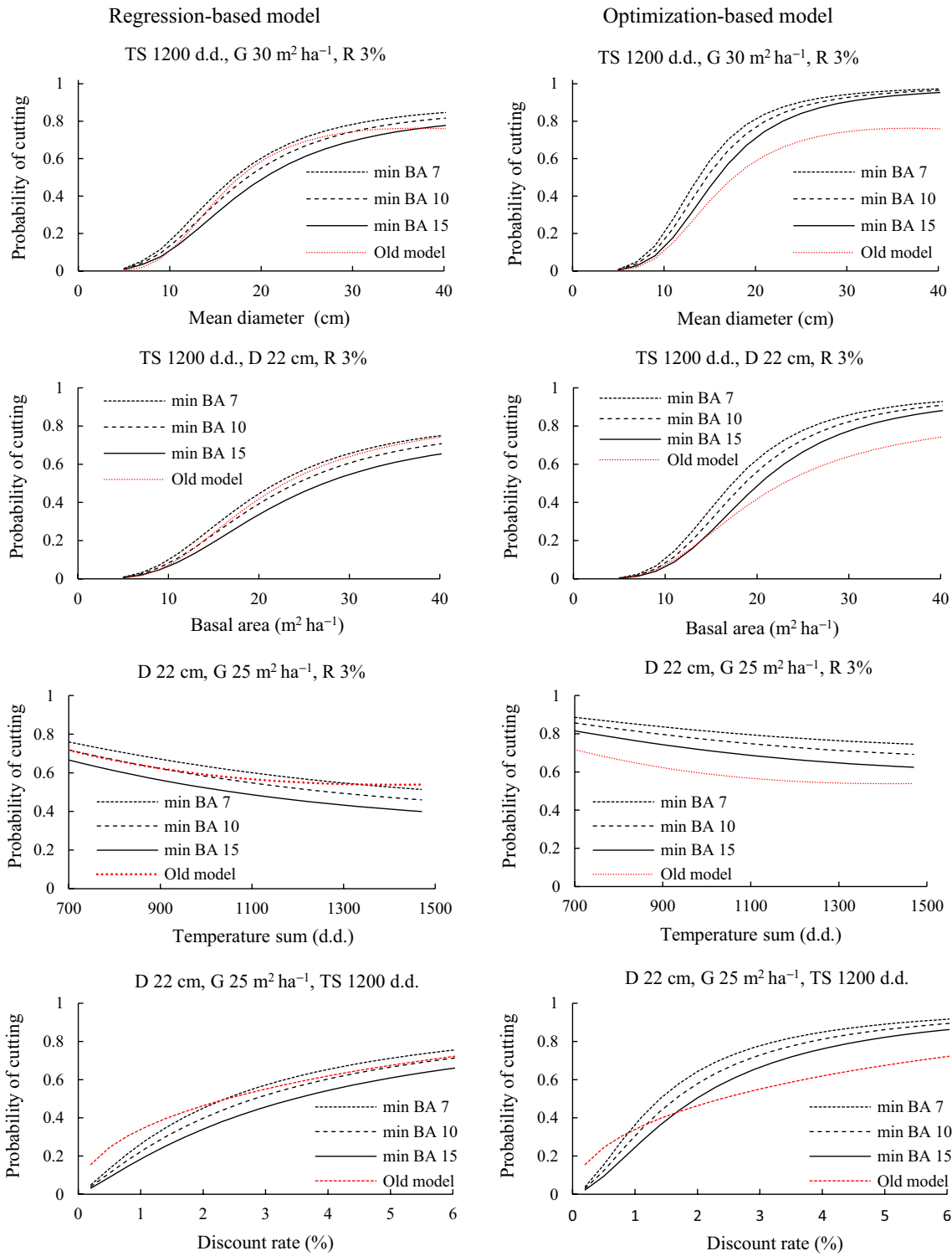


Fig. 2 The probability that harvesting is the optimal decision according to the models developed in this study and according to a previous model (Pukkala 2018). TS is temperature sum, D is mean diameter,

G is basal area R is discount rate and min BA is the lowest allowed post-thinning basal area (m² ha⁻¹)

that cutting is the optimal decision, which means that the maturity for cutting is reached with a larger mean diameter and stand basal area on fertile sites and in southern latitudes.

The minimum allowable post-thinning basal area also affected the optimal timing of harvesting. Decreasing the minimum basal area increased the probability that cutting the stand was the optimal decision. This means that cuttings are to be conducted earlier if the lowest allowable post-thinning basal area is low.

Of the two methods of fitting the model, the probability of cutting increases faster with increasing basal area and mean diameter in the optimization-based model. The predictions of the regression-based model resemble those of the earlier model (Pukkala 2018), whereas the optimization model predicts higher cutting probabilities. This means that the optimization-based model prescribes a cutting treatment earlier than the regression-based model or the earlier model.

Probability of thinning

The model for the probability that thinning is the optimal type of cutting (in the case where cutting is the optimal decision) was:

$$p_{\text{thin}} = \frac{1}{1 + \exp[-(X)]} \quad (13)$$

where

$$X = -11.9942 - 0.8459 \ln G_{\min} - 2.4844 \ln G - 0.1274D \cdot R + 3.2784 \ln TS - 8.3695 \ln R + 4.7947R + 0.8837G_{\text{pulp}} + 1.6442H + 1.4778M + 1.1575S \quad (14)$$

in the regression-based approach and

$$X = -8.2866 - 0.7132 \ln G_{\min} - 1.5673 \ln G - 0.1850D \cdot R + 3.5924 \ln TS - 7.8649 \ln R + 4.8114R + 6760G_{\text{pulp}} + 1.9676H + 0.6563M + 1.2537S \quad (15)$$

in the optimization-based approach. An additional predictor, compared to the model for the probability of cutting, is the basal area of pulpwood-sized trees (G_{pulp} , $\text{m}^2 \text{ha}^{-1}$). It is the basal area of trees whose dbh is 8–18 cm. A high basal area of pulpwood-sized trees greatly increases the probability that thinning is the optimal type of cutting instead of clear-felling (Fig. 3).

The probability that thinning is the optimal decision begins to decrease rapidly when the mean diameter of trees is > 25 – 28 cm. With smaller mean diameters, thinning is the optimal type of cutting with a very high probability. The probability of thinning increases with increasing temperature sums and site productivity, which means that thinning treatments should be extended to larger mean diameters at more

southern latitudes and on better-growing sites. Increasing the discount rate decreased the probability that thinning is the optimal type of cutting; if the opportunity cost of letting mature trees continue growing is high, it is optimal to cut all trees, even though the bare land value might be negative at a high discount rate.

A low minimum post-cutting basal area increased the probability that the optimal cutting type is thinning. This is logical, since the possibility to leave a sparse, post-thinned stand decreases the opportunity cost of the growing stock. Of the two versions of the model, the optimization-based variant prescribed thinning for a larger mean tree diameter. Also, the overall probability of thinning was higher with the optimization-based model. Compared to the earlier model (Pukkala 2018), the effects of mean tree diameter, discount rate, and temperature sums were stronger with the new models.

Models for the type of thinning

The models for the thinning type parameter of Eq. 1 were:

Regression-based model

$$a_1 = -24.956 + 13.559 \sqrt{D} - 1.596D \quad (16)$$

Optimization-based model

$$a_1 = -30.354 + 17.231 \sqrt{D} - 1.503D \quad (17)$$

According to these models, the value of parameter a_1 of the thinning intensity curve (Eq. 1) is always clearly positive with those mean diameters at which forests are thinned. This means that the models always prescribe thinning from above.

The models for parameter a_2 of the thinning intensity curve were:

Regression-based model

$$a_2 = \exp(0.4901 + 0.06083 \ln G_{\min} + 0.7651 \ln D - 0.1047 \ln G + 0.0823 \ln TS - 0.1218 \ln R + 0.0469H + 0.0572M + 0.0337S) \quad (18)$$

Optimization-based model

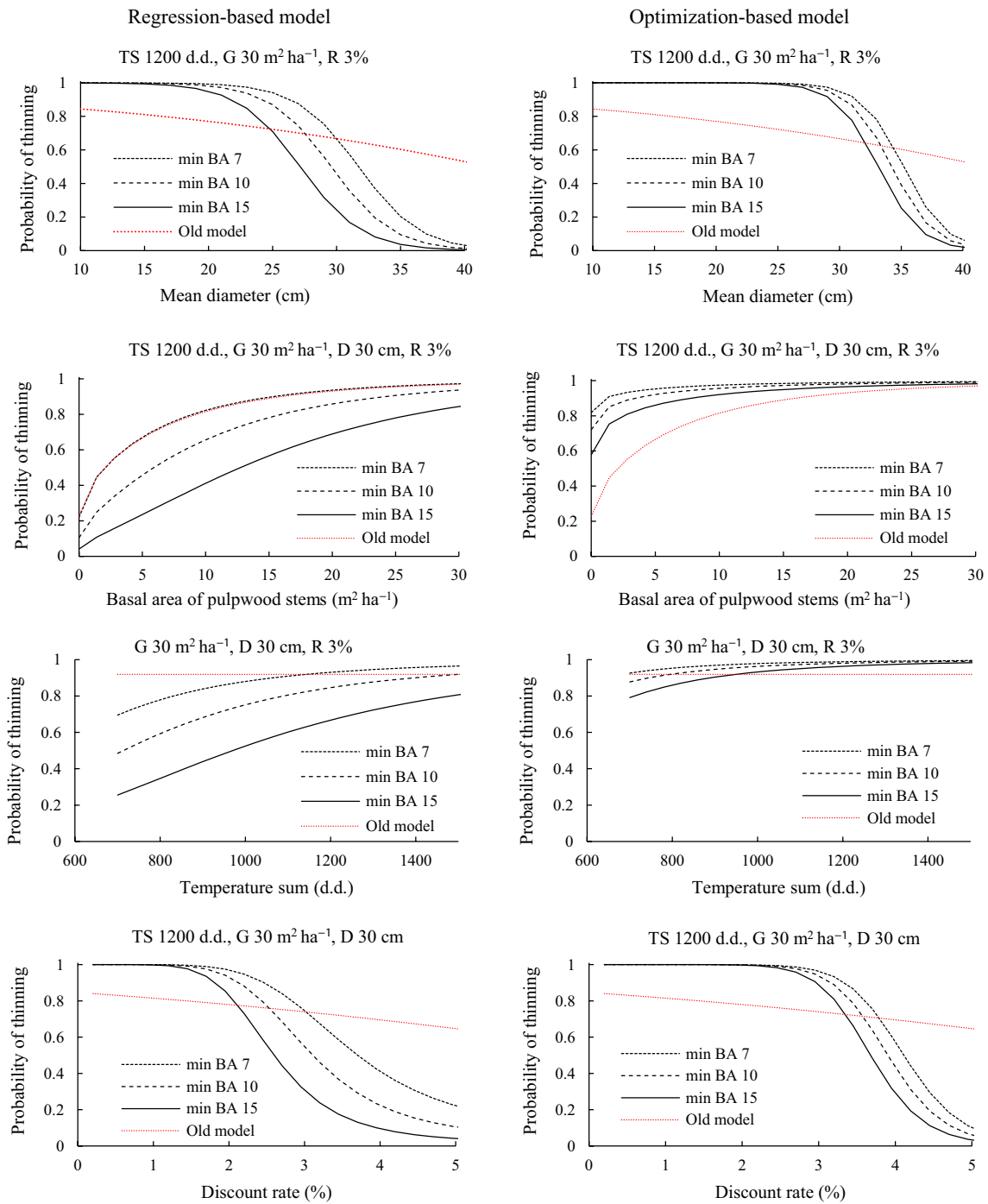


Fig. 3 Probability that thinning is the optimal type of harvesting (when harvesting is the optimal decision) according to the models in this study and according to a previous model (Pukkala 2018). TS

is temperature sum, D is mean diameter, G is basal area R is discount rate and min BA is the lowest allowed post-thinning basal area ($m^2 ha^{-1}$)

$$a_2 = \exp(0.4006 + 0.0594 \ln G_{min} + 0.7830 \ln D - 0.1173 \ln G + 0.0989 \ln TS - 0.1071 \ln R + 0.0408H + 0.0471M + 0.0333S) \quad (19)$$

Parameter a_2 is the diameter at which the thinning intensity is 50%. As thinning is from above, thinning intensity

is higher than 50% for dbh larger than a_2 and less than 50% for trees smaller than a_2 . Models 16 and 17 result in rather high values for parameter a_1 , which means that the thinning intensity increases sharply beyond a_2 and decreases sharply below a_2 . Therefore, the optimal cutting often resembles diameter-limit cutting.

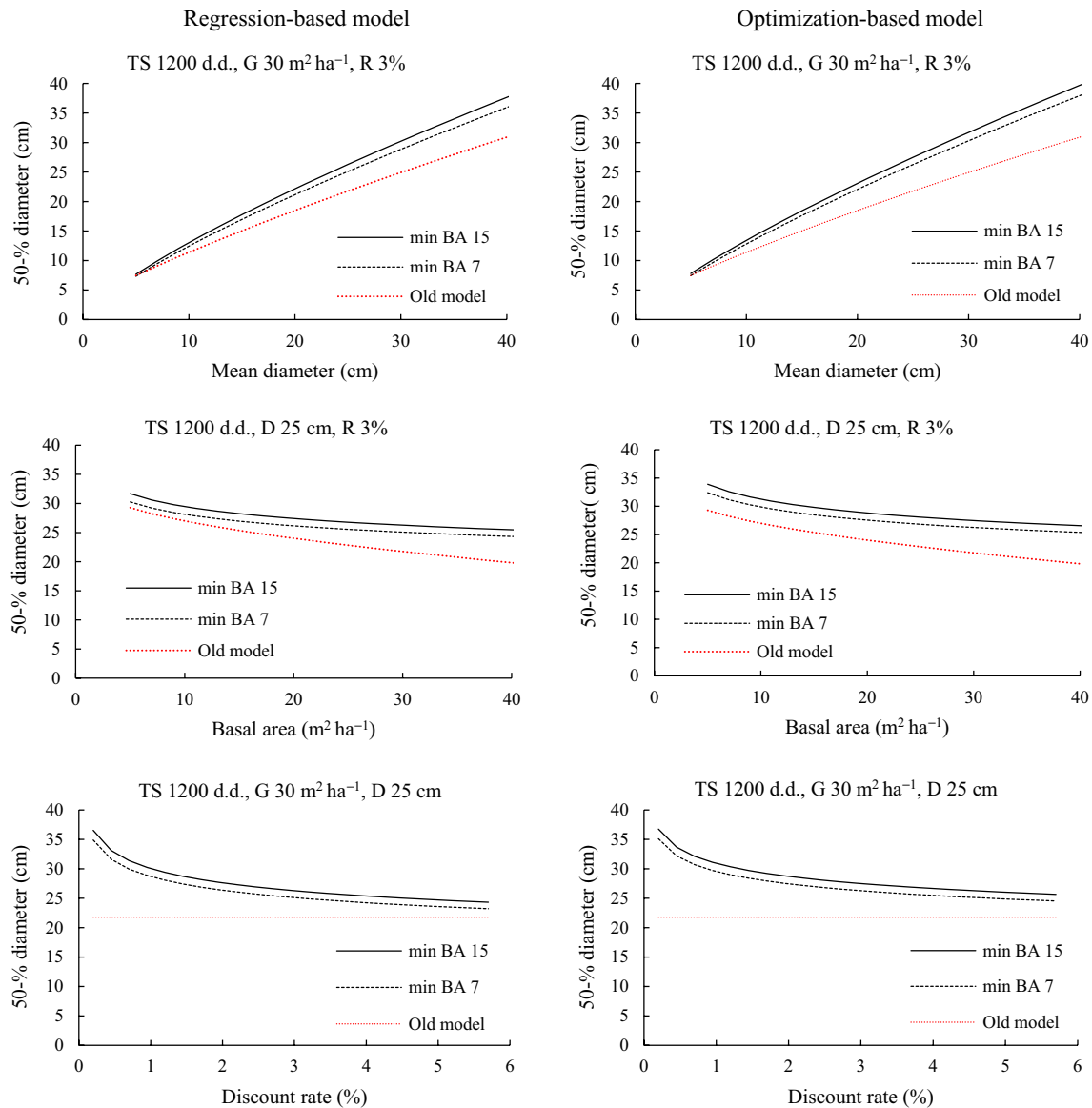


Fig. 4 Diameter at which thinning intensity is 50% according to the models in this study and a previous model (Pukkala 2018). TS is temperature sum, D is mean diameter, G is basal area R is discount rate and min BA is the lowest allowed post-thinning basal area ($\text{m}^2 \text{ha}^{-1}$)

Of the two versions of the model for a_2 , the regression-based model gives lower values compared to the optimization-based model, i.e., the regression-based model prescribes slightly heavier thinning (Fig. 4). Increasing discount rates lead to smaller a_2 , which means that thinning is heavier when the discount rate is high. Also increasing pre-thinning basal area increases the intensity of thinning. Both models suggest higher values for diameters at which thinning intensity is 50%, compared to the earlier models (Pukkala 2018). The effects of the models for a_1 and a_2 are visualized in Fig. 5 for two spruce stands growing on a mesic site in central Finland.

Test results for the models

The management of the 1651 stands was simulated using the regression- and optimization-based models to guide the simulation of harvesting. The same randomized discount rate, timber price, and minimum allowable post-thinning basal area were used in both simulations for a specific stand. The weighted sum of the net present values, calculated with Eq. 8, was 106 011 096 € when the regression-based models were used, and 128 797 744 € (21% higher) when the optimization-based models were used. This comparison suggests that the optimization-based guidelines would lead to better profitability.

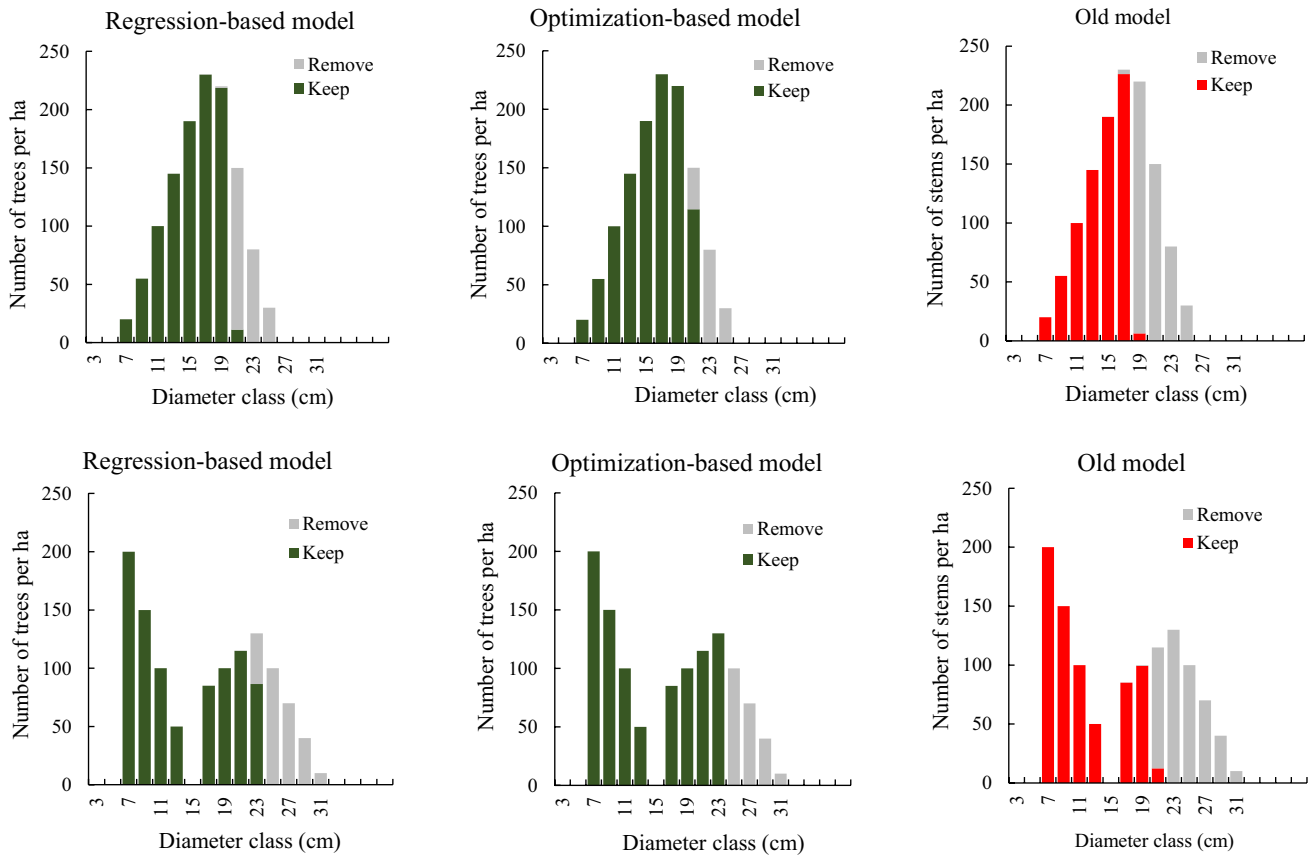


Fig. 5 Pre- and post-thinning number of trees in 2-cm diameter classes when thinning is simulated according to the models in this study and according to a previous model (Pukkala 2018). The temperature sum is TS 1200 d.d., the discount rate 3%, the lowest allowable post-thinning basal area 9 m² ha⁻¹ and the site is mesic. In the first stand (top), the pre-thinning basal area is 28.1 m² ha⁻¹ and its mean diameter 18.5 cm. The post-thinning basal areas are: regression-

based model 18.5 m² ha⁻¹, optimization-based models 22.5 m² ha⁻¹, and previous model 12.0 m² ha⁻¹. In the second stand (bottom), the pre-thinning basal area is 29.8 m² ha⁻¹ and the mean diameter 22.1 cm. The post-thinning basal areas are: regression-based model 15.7 m² ha⁻¹, optimization-based models 17.5 m² ha⁻¹, and previous model 8.5 m² ha⁻¹

Forest management plans are often developed so that treatments are simulated in the middle of a particular period, (for instance, a 10-year period), and not exactly in the year when the probability of harvesting exceeds 0.5. In addition, there might be a limitation that the cutting interval in the same stand should not be too short, meaning that the simulated management schedules may not follow the cutting instructions exactly. The usual procedure in forest planning is to simulate several alternative near-optimal management schedules and subsequently use combinatorial optimization to find the optimal combination of the schedules (e.g., Díaz-Yáñez et al. 2020). Combinatorial optimization makes it possible to consider constraints such as the requirement for even-flow of harvests as well as objective variables other than NPV.

The two sets of management instructions developed in this study were also compared in a forest-planning setting. This was carried out for two forest holdings, one representing the northern boreal forest and the other the southern

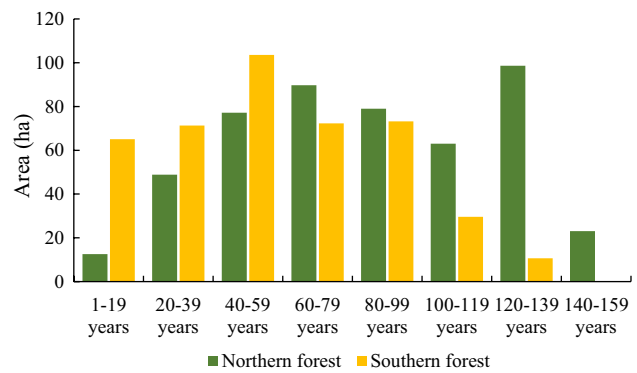


Fig. 6 Areas of age classes of stands in the northern and southern case study forests

boreal zone. The area of both holdings was approximately 420 ha, and both forests consisted of about 400 stands. The northern forests especially had a high percentage of stands

older than 100 years (Fig. 6). Pine was the dominant species whereas pine, spruce, and broadleaf species were of similar magnitude in the southern forest.

Alternative management schedules were simulated for the stands of these forests by varying the discount rate at which the instruction was used. These simulations used the same models for the stand dynamics, stem taper, harvesting costs, bare land value, and value of the residual forest used in the development of the management guidelines. The simulation was done using the instruction at 1%, 2%, and 3% discount rates. In addition, the limiting probability for thinning was varied in such a way that a harvest was simulated as a thinning when the calculated probability of thinning was higher than 0.4, higher than 0.5, or higher than 0.6. Harvesting was simulated when the probability of cutting being the optimal decision was 0.5 or higher. The simulation covered five 10-year periods. All harvests of a 10-year period were simulated at five years. The optimal combination of the simulated

management schedules was then selected by maximizing the total NPV calculated over the entire forest using a 2% discount rate.

To test the hypothesis that decreasing minimum post-cutting basal area improves profitability and decreases the use of clearcutting (Pukkala et al. 2014), the planning calculations were repeated with four levels of the lowest allowed post-thinning basal area, referred to as high, medium, normal, and low. A high level was 16 m² ha⁻¹ on herb-rich sites, 14 m² ha⁻¹ on mesic sites, 12 m² ha⁻¹ on sub-xeric sites, 11 m² ha⁻¹ on xeric sites, and 10 m² ha⁻¹ on the heath. The low levels were 10, 8, 6, 5, and 4 m² ha⁻¹ for herb-rich or better, mesic, sub-xeric, xeric, and heath sites, respectively. The other levels were in-between.

The guidelines of this study led to better NPV than the current management guidelines for even-aged forestry (Äijälä et al. 2014). However, the margin was small in the northern forests where the portion of financially mature

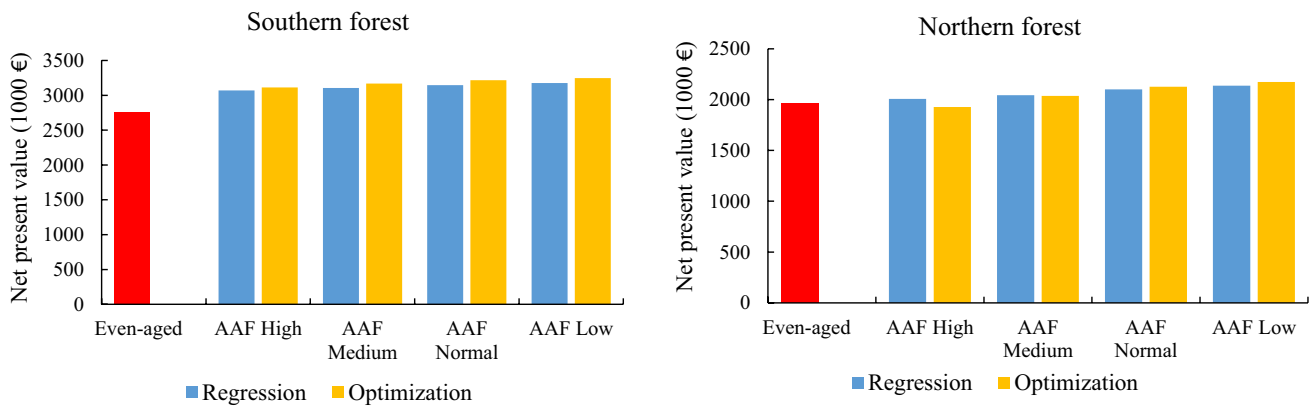


Fig. 7 Net present value calculated with a 2% discount rate in southern and northern boreal forests in even-aged and any-aged forestry (AAF) management when the lowest allowable post-thinning basal

area is high, medium, normal, or low. The treatments of the AAF system were prescribed using the regression-based or optimization-based guidelines developed in this study

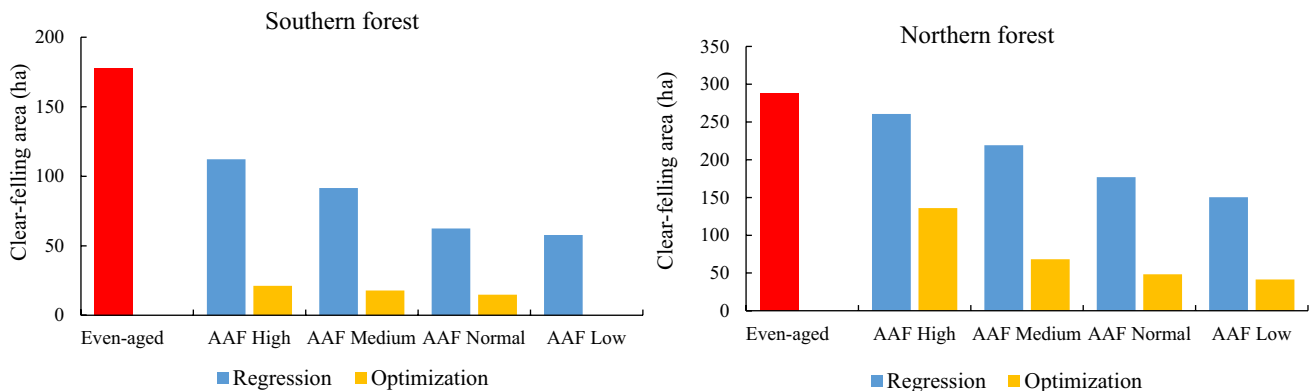


Fig. 8 Total clearcut area of the 50-year planning period in the southern and northern boreal forest in even-aged and any-aged forestry (AAF) when the lowest allowable post-thinning basal area is

high, medium, normal, or low; treatments of the AAF system were prescribed using the regression-based or optimization-based instructions developed in this study

stands was high, especially when the lowest allowable post-thinning basal area was high. The analysis confirms the hypothesis that decreasing the minimum post-thinning basal area improves the profitability of forest management (Fig. 7). The other hypothesis that decreasing minimum post-thinning basal area leads to decreased use of clear-felling, was also strongly supported (Fig. 8).

Of the two sets of management guidelines developed in this study for AAF, the optimization-based ones led to higher NPV. The exception was the northern forest with a high minimum post-thinning basal area. The optimization-based instructions prescribed less clear-felling than the regression-based ones.

Discussion

The management guidelines developed in this study are based on the concept that decisions on forest management are taken one at a time. They are based on long-term optimizations of several future harvests, which means that the prescription is based on both immediate and long-term consequences of the decision. However, the models advise only what the optimal decision would be now. Pukkala (2018) showed that following these management instructions lead to equally high NPV as optimizing a sequence of future cuttings. However, using the guidelines is easier than the use of sophisticated optimization methods.

The guidelines developed in this study have one advantage over long-term optimizations. The optimal time and type of a future harvest depend on how the forest develops, and the actual development may differ from what the models predicted. For example, it is not possible to accurately predict the future ingrowth or natural regeneration since they depend on variables that cannot be reliably predicted. For example, the size of seed crops, germination of seeds and survival seedlings depend on weather and other factors in complicated ways (Pukkala et al. 2010; Manso et al. 2013). Therefore, it might be unwise to decide or fix the management schedule of a forest stand for the distant future.

Another starting point for the guidelines developed in this study was that no choice is required between CCF and RFM. Because all cutting types used in CCF and RFM are acceptable, optimized AAF results in equal or better profitability than restricting management to follow either RFM or CCF or assigning stands permanently to one of these silvicultural systems (Díaz-Yáñez et al. 2020). The reason for the superiority of AAF is that it is more flexible and less constrained than RFM or CCF. The names given to this type of management, namely any-aged management (Haight and Monserud 1990a) or freestyle management (Boncina 2011), refer to this flexibility.

In addition to providing updated guidelines for any-aged forest management, this study also developed new models for bare land valuation (Appendix 1) and the valuation of forested land (Appendix 2). These models can be used in forest planning calculations, optimization studies, and in the evaluation of the economic value of a forest estate. These models consider both the discount rate and timber price, both of which may vary temporarily and geographically.

The optimization-based variant of the new AAF guidelines propose lighter thinning and less frequent use of clearcutting, compared to the regression-based variant. The reasons for the difference are related to the fitting method and objective function. The regression method first optimizes the management of a set of stands separately and then fits each sub-model of the instruction separately by maximizing the fit of the model. The optimization-based system, on the other hand, fits all models simultaneously in a single step, maximizing the net present value calculated over all the stands of the dataset.

The test results suggest that the optimization-based approach leads to more profitable forest management. The optimization based AAF guidelines indicate that forests should be managed mainly with thinning from above, and harvest intensities are moderate. Therefore, the same stand should be thinned frequently. It may be concluded that if harvesting costs are ignored or timber is sold at a fixed stumpage price, optimal management would involve many light thinnings, each removing trees that have reached or are approaching financial maturity (their relative value increment is lower than the required rate of interest). The true optimum depends on how the harvesting costs per cubic meter is related to harvested volume per hectare.

Compared to the earlier AAF guidelines for Finnish forests (Pukkala 2018), the lowest allowable post-thinning basal area was used as an additional predictor in the decision rules. This value is dictated by forestry legislation, but it can be set higher than the legal limit to decrease the risk of wind damage or increase the growing stock volume for other reasons. Of the two versions of the new AAF guidelines, the optimization-based version is better in windy regions as these instructions advise to gradually decrease stand density in repeated thinnings. These thinning treatments allow the trees to gradually expand their root systems and strengthen their stems without making the stand too vulnerable to wind damage.

The effect of the minimum post-thinning basal area was as expected, based on earlier research (Pukkala et al. 2014). Decreasing the lowest allowable post-thinning basal area improved profitability and decreased the use of clearcutting.

From a landscape-ecological point of view, the use of the models of this study results in forest management where there are both severe (clearcutting) and mild (thinning) disturbances. Contrary to using only CCF in all stands,

AAF generates open areas and initiates even-aged cohort dynamics which can be found also in unmanaged Fennoscandian forests (Berglund and Kuuluvainen 2020). On the other hand, the AAF guidelines result in less clearcutting compared to the current even-aged management (Fig. 8). Even-aged management produces fewer uneven-sized stand structures compared to natural disturbance dynamics (Kuuluvainen 2009). Therefore, forests managed according to AAF guidelines produce forest landscapes that are closer to natural landscapes compared to using CCF or RFM alone (Berglund and Kuuluvainen 2020).

A mixture of different forest structures and silvicultural systems may be the best way to guarantee a sustainable supply of most ecosystem services (Triviño et al. 2016; Peura et al. 2018; Díaz-Yáñez et al. 2020; Eyvindson et al. 2020). On the other hand, the use of AAF does not guarantee the viability of the populations of all forest-dwelling species (Mönkkönen et al. 2011). Any type of management that aims at good economic profitability tends to increase conifer volumes and decrease the volume of deadwood and large trees. Protected areas, green-tree retention, and other measures are therefore necessary to maintain the biodiversity of boreal forests (Mönkkönen et al. 2011).

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