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Plenterwald, Dauerwald, or clearcut?

Timo Pukkala

University of Eastern Finland, PO Box 111, 80101 Joensuu, Finland

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ABSTRACT

Forest landowners are interested in management alternatives which do not involve clearfelling and planting. Also many citizens that do not own forest are against clear-felling do to its harmful effects on amenity values and ecosystem services. Most studies on continuous cover forest management (CCF) deal with regular, steady state uneven-aged forests (Plenterwald), or with the conversion of stands into steady-state structure. However, people who want CCF management seldom want Plenterwald in particular; continuous tree cover would in most cases be sufficient. This type of management corresponds to the German Dauerwald concept. This study compared the profitability of Plenterwald, Dauerwald and clear-cutting schedules in Finnish spruce forests. As expected, Dauerwald was more profitable than cutting schedules that converted the stand into steady-state Plenterwald structure. The difference in net present value decreased with increasing number of conversion cuttings. Clear-cutting and planting was more profitable than optimal CCF only in a mature initial stand when the planted spruces were assumed to grow 20% faster in dbh and height, compared to naturally regenerated spruces. In young, medium-aged and uneven-aged initial stands, CCF was more profitable even when 20% tree breeding benefit was assumed in the plantation that was established in the clear-felling site.

1. Introduction

Continuous cover forestry (CCF) is one of the current megatrends in forest management (O'Hara et al., 2007; Schütz et al., 2012). CCF corresponds to the German Dauerwald concept, which according to Alfred Möller (Möller, 1922; Helliwell, 1997) can be characterized as follows: avoid clear-felling; minimize capital; maximize production; remove trees of decreased vigor; do not aim at any pre-defined steady-state forest structure; leave cutting residues in the forest; and rely on natural regeneration. Dauerwald is different from Plenterwald (Schütz, 2001), or uneven-aged management, which aims at a certain steady-state forest structure and often assumes that exactly similar cuttings can be repeated at regular intervals to infinity.

Few forest landowners actually want Plenterwald or a certain forest structure. What they want is in most cases a continuous cover of trees with no clear-felling and planting, more natural-looking forests, and less intensive forest management (Valkeapää et al., 2009; Diaci et al., 2011; Asikainen et al., 2014). Therefore, studies which optimize the steady-state management of uneven-aged forest (Chang, 1981) or aim at finding the optimal sequence of transformation cuttings to steady-state forest structure (Haight et al., 1985) may not be the most useful for forestry practice.

When the management objective is to maintain continuous tree cover and use less intensive management the task of forest planning is simply to find the most profitable management schedule that meets these criteria. This schedule may or may not converge to steady-state stand structure. Steady-state structure is a constraint, which can only decrease profitability compared to non-constrained management (Haight, 1987). The sooner the steady-state structure must be reached the lower is the profitability of forest management. Constrained management regimes that involve obligatory clear-cutting and planting are also sub-optimal relative to more general problem formulations (Haight, 1987).

Legislation may set limits to the optimization of forest management. For instance in Finland and Sweden, the national forest law forbids the landowner to reduce the growing stock volume (Sweden) or stand basal area (Finland) below certain limits (Wikström, 2008; Laki

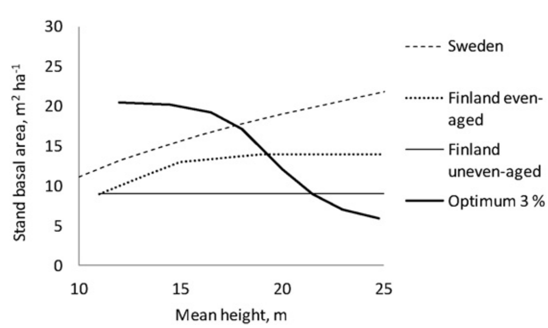

Fig. 1. Minimum stand basal area according to Finnish and Swedish legislation (the Swedish volume limit has been converted into basal area limit). The thick line shows the basal area which maximizes the difference between annual value increment and opportunity cost in a spruce stand growing in Central Finland. Opportunity cost is equal to 3% of the stumpage value of growing stock and bare land value (1000 €/ha).

E-mail address: timo.pukkala@uef.fi.

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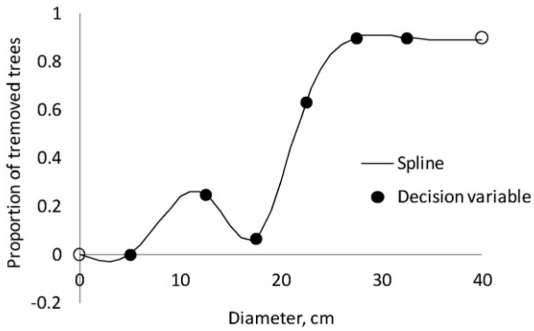

Fig. 2. Optimized decision variables (filled dots) and a cubic spline function used to calculate the harvest percentage for individual trees. Negative values were replaced by zero and values greater than 1 were replaced by 1. Open circles are additional points (one at both ends) used for fitting the spline.

metsälain muuttamisesta, 2013). Interestingly, the minimum allowed volume or basal area of an even-aged stand increases with increasing tree size, although the economically optimal stocking level would decrease with increasing tree size (Fig. 1). This means that legislation constraints economically optimal management more in mature stands than in stands of young and small trees.

Thinning treatments improve profitability if they reduce the opportunity cost of growing stock relatively more than they decrease value increment. Thinnings from above (high thinnings) are the best means to achieve the wanted effect since they remove mainly trees with high opportunity cost and low relative value increment, and leave trees with low opportunity cost and high relative value increment (Knoke, 2012).

When tree size increases the opportunity cost of the capital invested in wood production also increases, but the inherent growth rate of trees usually decreases, calling for decreasing the growing stock volume with increasing tree size. Since the minimum legal stand volume or basal area increases with mean tree size, legislation reduces the possibilities to improve profitability through thinning treatments especially in mature stands. Legislation forces the landowner to face so high opportunity costs in mature stands that clearfelling may become optimal even when it is followed by obligatory planting, which as such would not be profitable. Without legislation, the true optimum would in most cases be to thin the stand below the legal limit and let it regenerate naturally (Pukkala et al., 2014a). Natural regeneration is not forbidden, but the Finnish forestry legislation sets another constraint requiring that a sufficient regeneration must be obtained within a certain time frame. This may not always be possible, or there is a high probability that regeneration is not fast enough from the legal point of view.

Cheaper harvesting and the possibility to benefit from tree breeding are the advantages of clear-felling and planting. If the savings in harvesting and the increase in growth rate are large enough, clear-felling and planting may be the most profitable management option even without legislation and despite the fact that it includes additional silvicultural costs as compared to CCF.

This study compared the profitability of three management options in different initial stands under the current forest legislation of Finland (1) CCF, (2) conversion of the stand into steady-state uneven-aged structure; and (3) clear-felling and planting. The effect of tree breeding was considered in the analysis. It was hypothesized that increasing tree size in the initial stand increases the relative profitability of clear-felling and planting. CCF (Dauerwald) as a less constrained management system was assumed to be more profitable than conversion into steady-state uneven-structure (Plenterwald). The sooner the steady-state structure must be reached the lower should the profitability of the conversion schedule be.

2. Materials and methods

Four Norway spruce stands growing on fertile site in Central Finland were selected for the analyses (Table 1). In the young stand no trees had reached the saw-log size, and in the mature stand all the trees were already saw-log sized. In the medium-aged stand, about half of stand basal area was in pulpwood-sized trees and the rest was in saw-log sized trees. The fourth stand was uneven-aged (two layered), consisting of two strata, both of which had plenty of variation in tree size.

The trees harvested in cuttings were partitioned into saw-logs, mini logs, and pulpwood pieces (Table 2). The income from harvesting was calculated as the difference between roadside timber prices (Table 2) and harvesting cost. Harvesting costs were calculated with the models of Rummukainen et al. (1995). These models predict lower unit costs in clear-felling than in thinning when the removal per hectare and the mean size of harvested trees are the same. Harvesting cost per cubic meter decreases with increasing size and per hectare volume of harvested trees.

The stand data were used to predict the diameter distribution of each stratum of the stand. Then, 50 representative trees per stratum were drawn from the distribution to represent the stand in simulation. The models of Pukkala et al. (2013) for diameter increment, survival and ingrowth were used to simulate stand dynamics:

Diameter increment:

$$id = \exp(-9.645 + 0.455\sqrt{d} - 0.0574d + 1.455\ln(TS) + 0.291OMT - 0.049VT - 0.404CT - 0.308\ln(G) - 0.029\frac{BALp}{\sqrt{d+1}} - 0.142\frac{BALs}{\sqrt{d+1}} - 0.083\frac{BALh}{\sqrt{d+1}})$$

where *id* is the future 5-year diameter increment (cm), *d* is diameter at breast height (cm), *TS* is temperature sum (degree days), *G* is stand basal area (m^2ha^{-1}), *BALp*, *BALs* and *BALh* is the basal area in larger pines, spruces and hardwood species, respectively (m^2ha^{-1}), and *OMT*, *VT* and *CT* are indicator variables for herb-rich, sub-xeric and xeric site, respectively.

Table 1
Initial stands.

Stand “name”	Stratum	Basal area, m^2 ha^{-1}	Mean height, m	Diameter, cm		
				Minimum	Mean	Maximum
Young	1	15.0	11	5	12	18
Medium	1	25.0	16	11	18	26
Old	1	25.0	22	18	25	30
Uneven	1	15.0	21	18	22	28
	2	7.6	6	1	8	16

Table 2
Assortments and their roadside prices.

Assortment	Roadside price, € m^{-3}	Minimum top diameter, cm	Minimum piece length, m
Pulp wood	28	8	3.0
Mini log	32	13	4.3
Saw-log	55	16	4.3

Survival probability:

$$s = \frac{1}{1 + \exp\left(-\left(5.871 + 1.536\sqrt{d} - 0.122d - 0.106\sqrt{BALp} - 0.690\sqrt{BALs} - 0.226\sqrt{BALh} - 0.465 Period\right)\right)}$$

where s is the probability of survival and *Period* is the length of the projection period (years).

Probability of ingrowth:

$$p_{in} = \frac{1}{1 + \exp(-(1.001 + 0.661\ln(G_{spruce}) + 0.046G_{pine} - 0.066G - 0.814CT))}$$

where p_{in} is the probability that there is ingrowth during the coming 5-year period, G_{spruce} is the basal area of spruce (m^2ha^{-1}), G_{pine} is the basal area of pine (m^2ha^{-1}), G is the total stand basal area (m^2ha^{-1}), and CT is indicator variable for xeric site.

Number of ingrowth trees:

$$\ln(N_{in}) = 4.378 - 0.0265\sqrt{G}$$

where N_{in} is the number of ingrowth trees per hectare during 5 years (in case there is ingrowth) and G is stand basal area (m^2ha^{-1}). In the simulations of this study, the number of ingrowth trees was obtained as the product of p_{in} and N_{in}. The ingrowth trees were added to the set of representative trees: one new cohort (representative tree) was added per 10 conifers or 50 broadleaf trees per hectare. Mortality was simulated by multiplying the frequencies of representative trees by their survival probabilities. Taper models (Laasasenaho, 1982) were used in volume calculations.

The sequence of two to seven cuttings was optimized. Each cutting was specified by cutting year and harvest percentages of different 5-cm diameter classes. The optimized variables were the class specific harvest percentages but when the cutting was simulated, spline-smoothing was used to get the harvest percentage individually for each representative tree (Fig. 2). Among alternative ways to optimize thinning intensity, spline-smoothed intensities for different diameter classes have been found to result in higher NPVs than alternative formulations (Pukkala et al., 2014a).

When optimizing conversion into uneven-aged steady-state structure, 2 to 5 conversion cuttings were allowed. The last cutting had to produce a steady state post-cutting diameter distribution: all subsequent cuttings returned the diameter distribution to that obtained in the last optimized cutting. The periodical income from the steady state forest was calculated by simulating an additional 15-year cutting cycle. The NPV of an infinite series of steady-state cuttings was added to the NPV of the optimized cuttings. This problem formulation produced the optimal steady-state structure simultaneously with the transformation cuttings (Haight and Getz, 1987).

In CCF, the next cuttings were optimized without any requirement for steady state (Haight and Monserud, 1990). The value of the ending growing stock (NPV of all future cuttings) was calculated with a model (Pukkala, 2005). It was first examined how many cuttings need to be optimized so that the NPV and the thinning intensity of the first cuttings stabilize, i.e. possible errors in the model for growing stock value stop affecting the results. It was found out that it is enough to optimize 5 or 6 cuttings (and calculate the NPV of later net incomes with a model) to obtain a reliable NPV estimate (Fig. 3) and know how the stand should be managed in the first three to four cuttings (Fig. 4). Therefore, the results presented for CCF are based on the optimization of six next cuttings.

The model used to calculate the value (NPV) of the ending growing stock is an up-dated version of an earlier model (Pukkala, 2005), which was developed for even-aged management and assumed that similar rotations are repeated to infinity. The up-dated model is for any type of management and it is based on the NPVs optimal 30-year management schedules (representing either even-aged or uneven-aged management) for a high number of stands locating in different parts of Finland. In these schedules, the NPV after the 30-year period was calculated with the original model (Pukkala, 2005). The optimal schedules were selected separately for different discount rates and timber prices, resulting in about 70,000 observations for fitting the model. NPV was predicted from site characteristics, stand basal area, mean tree diameter, species composition, discount rate, and timber prices. The model explained 92.1% of the variation in the NPVs of the optimal schedules.

In all cuttings, a minimum residual basal area was required (9 m^2/ha), corresponding to the current Finnish legislation for uneven-aged stands. Solutions resulting in lower basal area were penalized, preventing the selection of such schedules.

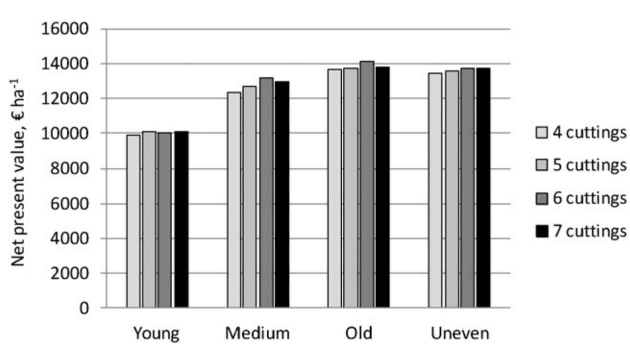

Fig. 3. NPV of CCF as a function of the number of optimized cuttings when the NPV of the ending growing stock (NPV of all future cuttings) is calculated with a model.

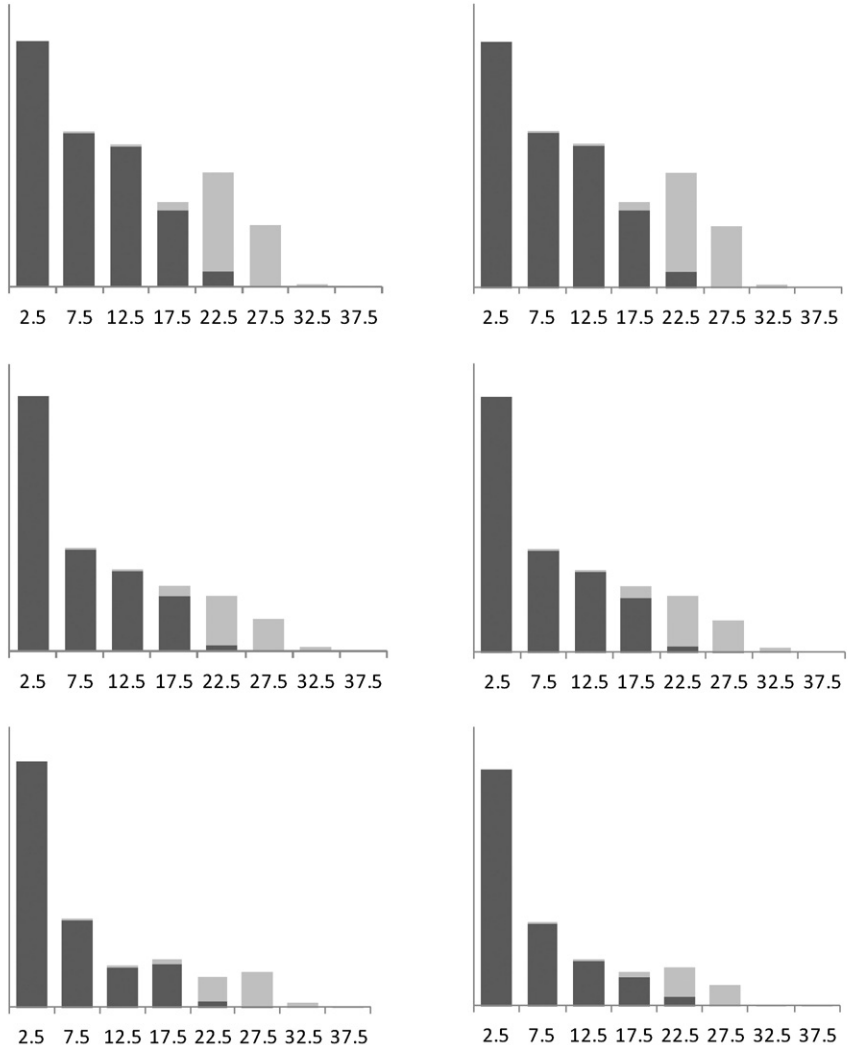

Fig. 4. Similarity of the first (top), second (middle) and third (bottom) cutting of an uneven-aged initial stand when four (left) or six (right) first cuttings were optimized and the NPV of the ending growing stock (value of post-cutting stand after the fourth or sixth cutting) was calculated with a model. Remaining trees in different 5-cm diameter classes are indicated with dark tone and removed trees are shown with light gray.

To obtain even-aged management schedules the minimum basal area was raised to 14 m^2/ha, which corresponds to the legal limit for even-aged management. In addition, no partial cuttings were allowed if the mean tree diameter was 25 cm or more. These settings resulted in the selection of clearfelling for each initial stand, either immediately or after one or several thinnings. After clearfelling, cleaning the site from advance regeneration and non-commercial small trees, site preparation, planting of spruces and tending of the young plantation were simulated. The total cost of these treatments was assumed to be 1900 €/ha (cleaning 250 €/ha, site preparation 300 €/ha, seedlings and planting 1000 €/ha, tending 350 €/ha). A tree breeding multiplier of 1.2 was assumed for planted spruces in a part of optimizations: height and diameter growths predicted by the models were multiplied by 1.2. Six cuttings were optimized in even-aged management, and the NPV of the ending growing stock was calculated with the same model as used in CCF.

The used discount rate was 3% except when the effect of discount rate on the results was analyzed.

3. Results

3.1. Plenterwald vs. Dauerwald

As expected, optimal CCF resulted in higher NPV than optimal conversion to steady-state uneven-aged structure (Fig. 5). The higher was the number of conversion cuttings, the closer was their NPV to the NPV of CCF. Fig. 5 shows that young and medium-aged stands needed 4 or 5 conversion cuttings to have NPVs close to that of the optimal CCF. The length of the conversion period was not necessarily shorter for fewer conversion cuttings (Table 3). Usually, the interval between cuttings increased when the number of conversion cuttings decreased.

As expected, optimal conversion cuttings removed predominantly large trees (Fig. 6). It is noteworthy that some of the large trees of the

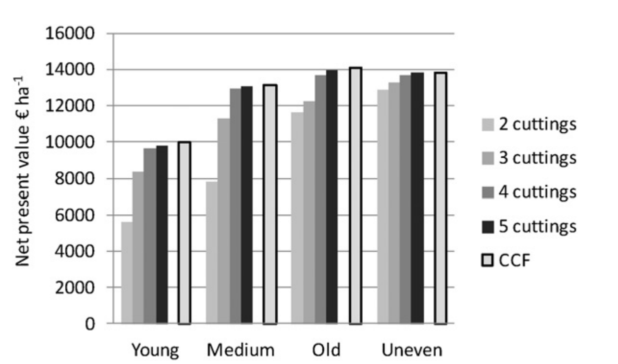

Fig. 5. Net present value of conversion cuttings compared to optimal CCF when a steady state diameter distribution must be reached in 2, 3, 4 or 5 cuttings.

Table 3
Length of the conversion period as a function of the number of conversion cuttings (number of years since the start of simulation). The number in parenthesis is the time between the first and last conversion cutting. The last conversion cutting results in a steady-state stand structure.

Number of conversion cuttings	Initial stand			
	Young even-aged	Medium-aged	Old even-aged	Uneven-aged
2	105 (70)	120 (100)	40 (35)	25 (15)
3	85 (65)	70 (60)	75 (70)	35 (30)
4	70 (50)	65 (55)	60 (60)	55 (45)
5	80 (60)	65 (55)	80 (80)	60 (60)

old initial stand were maintained in the second and third cutting although there were already more than 1200 new small trees per hectare when the second cutting was conducted. The obvious reason was the minimum required stand basal area of 9 m^2/ha. In addition, large trees promoted regeneration and ingrowth. When the number of conversion cuttings was four, the first cutting was immediately in the old (mature) stand, after 10 years in the medium-aged stand, and after 20 years in the young stand. Cutting intervals ranged from 10 to 30 years. The total conversion time (interval between the first and the fourth cutting) was

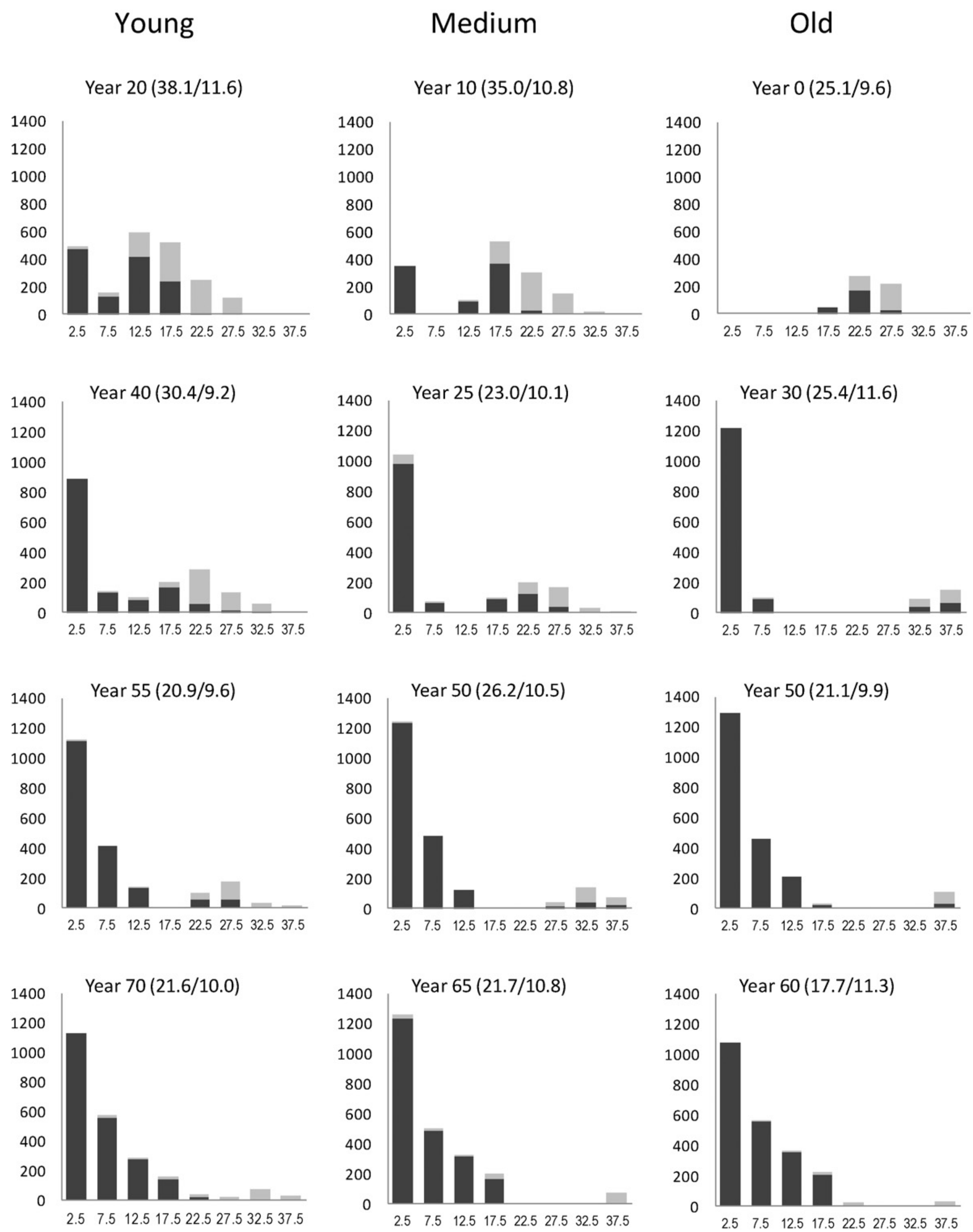

Fig. 6. Optimal timing and type of cuttings for young (left), medium-aged (middle) and old (right) initial stand when a steady-state diameter distribution must be reached in four cuttings. Pre- and post-cutting stand basal areas (m^2 ha^{-1}) are shown in parentheses.

50 years for the young initial stand, 55 years for the medium-aged stand, and 60 years for the old stand.

The post-cutting basal area was mostly around 10 m^2/ha, i.e., slightly more than the legal minimum. Most probably the legal limit influenced both the timing and intensity of cuttings although the post-cutting basal area was not exactly 9 m^2/ha. When the stand included also small trees with very low opportunity cost, the importance of reducing the stand basal area to exactly 9 m^2/ha was less important than it would be in even-sized stand consisting of large trees.

The steady stage stand structure and the management of the stand after the last conversion cutting depended on the initial stand although the growing site (fertility and temperature sum) was the same for all stands (Fig. 7). The pre-thinning basal area of the steady-state stand varied from 17.7 to 24 m^2/ha and the basal area of the post-cutting steady-state stand ranged from 10.0 to 11.5 m^2/ha when the cutting cycle was 15 years. Almost all removed volume consisted of trees of 20 to 30 cm in dbh (class midpoints 22.5 and 27.5 cm). In young and uneven-aged initial stands, steady state management involved leaving a few trees in diameter class 20–25 cm whereas in the other initial stands the largest trees of the residual stand belonged to class 15–20 cm.

There were no large differences in the pre- and post-cutting basal areas between optimal CCF and optimal conversion cuttings (Fig. 8). The examples shown in Fig. 8 are for five conversion cuttings. Both pre- and post-cutting basal areas decreased with increasing mean size of the trees. In the young initial stand the basal areas have a decreasing trend because the trees get larger. The opposite happens in the old initial stand where mean tree size begins to decrease after the removal of old trees and as a consequence of ingrowth. In general, the post-cutting basal area was close to the legal minimum (9 m^2/ha) when the mean tree size was large.

3.2. Profitability of clearfelling

The optimal clear-felling schedule was more profitable than optimal CCF only in one case: when the initial stand was mature and the planted trees were expected to grow 20% faster in dbh and height (for their whole life) than naturally regenerated trees (Fig. 9). The difference in favor of CCF was largest in the uneven-aged initial stand. Since volume is a 3-dimensional characteristic a 20% tree breeding benefit in 1-dimensional variable should result in much larger relative gain in volume production. For example, in the old initial stand the volume growth of the new plantation improved by 47% during the first 35 years, compared to plantation in which there was no tree-breeding effect. However, the volume production of the whole simulation period (6 cuttings) was only 22% higher when breeding effect was assumed. This is because competition and increasing tree size started to decrease growth sooner when the growth rate of trees was fast.

All thinnings were high thinnings (thinning from above) also in even-aged management (Fig. 10). However, it often happened that trees were removed from both ends of the diameter distribution, especially in thinnings that preceded the clear-felling. Optimizations suggested that it was often profitable to remove all non-commercial small trees. These trees may not reach large enough size by clear-felling and they may decrease the net income from clear-felling due to the high harvesting cost of small trees. The remaining basal area of the last thinning prior to clear-felling was always exactly 14 m^2/ha, i.e. equal to the legal limit for even-aged management. This suggests that the legal limit decreased the profitability of clear-felling schedules.

3.3. Effect of discount rate

In CCF, lower discount rate led to higher pre- and post-thinning stand volumes (Fig. 11) and basal areas. The effect of discount rate was very clear in all initial stands except the old one. Most probably the legal limit constrained the optimization of this stand with all discount rates. However, higher rate shortened cutting intervals also in this stand. Later-on, when all trees of the initial stand had already been removed, the optimal CCF with 1% and 5% rate started to deviate more. Increasing the discount rate from 1% to 5% decreased the basal-area-weighted mean dbh of the pre- and post-cutting stand by

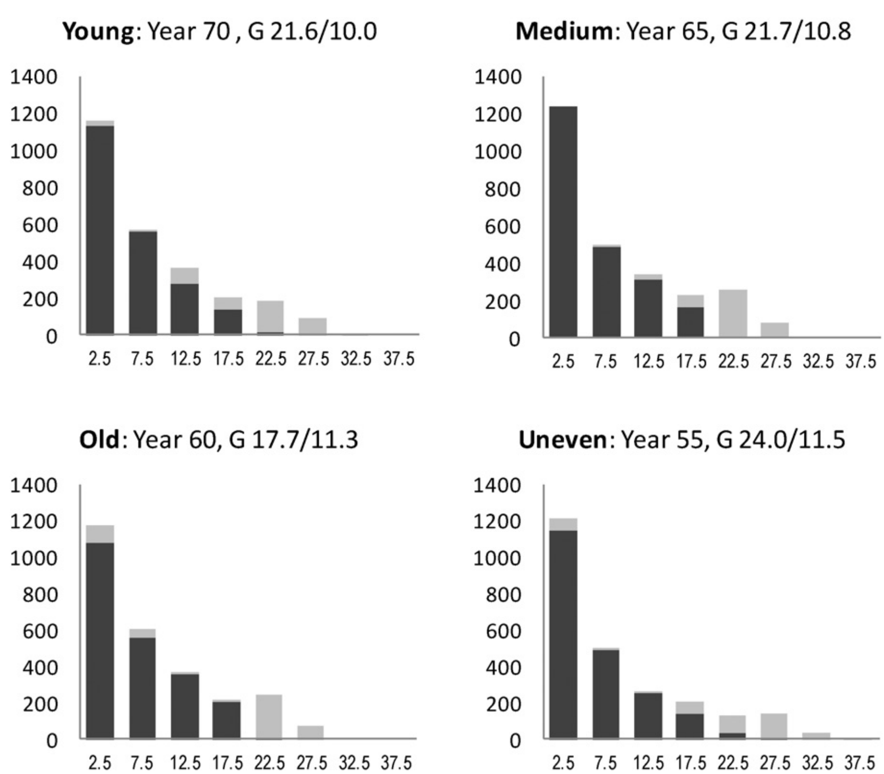

Fig. 7. Optimal pre- and post-cutting steady state distributions for different initial stands when the steady state must be reached in four cuttings (dark tone: remaining trees; light tone: removed trees). Year is the number of years since beginning to the fourth cutting, and G is stand basal area before/after cutting (m^2 ha^{-1}).

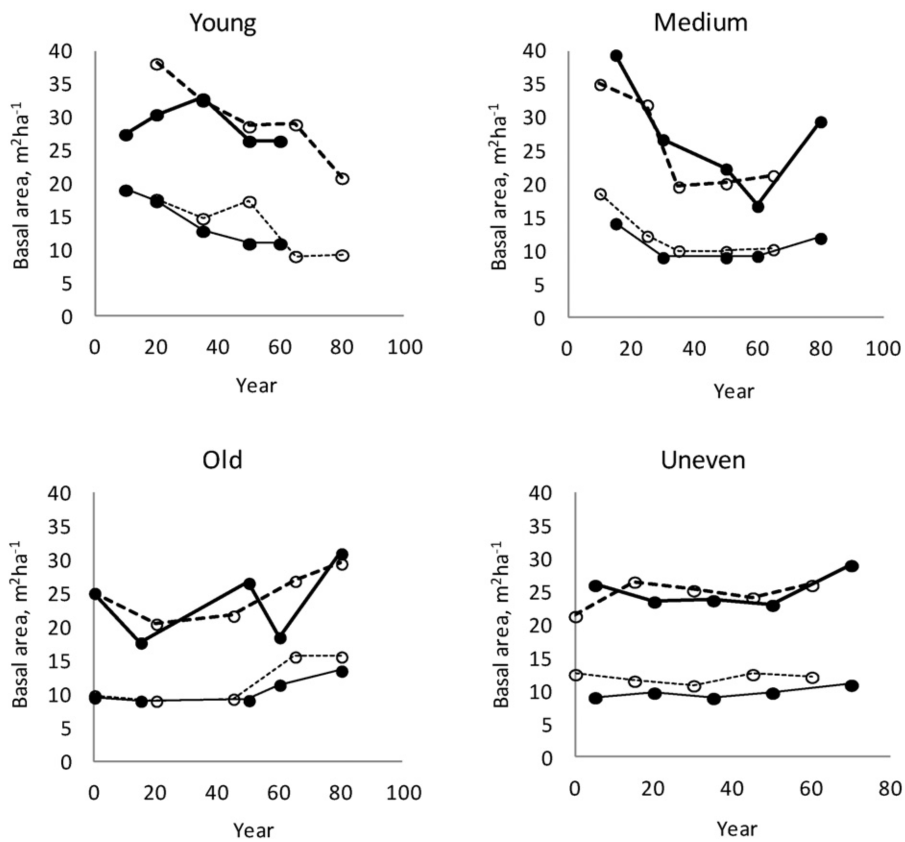

Fig. 8. Sequence of pre-cutting (thick lines) and post-cutting (thin lines) basal areas in optimal CCF (continuous lines) and optimal conversion cuttings (dashed lines) when a steady state diameter distribution must be reached in the 5th cutting.

2–5 cm. As a consequence of decreased tree size and stand volume, the stumpage value of the post-cutting was clearly lower with 5% discount rate, typically around 40% of the value obtained with 1% rate.

Discount rate (1, 3 or 5%) did not alter the ranking of CCF and even-aged (clear-felling) schedules. In the young and medium-aged initial stands the NPVs of the clear-felling and CCF schedules were close to each other with all discount rates if tree-breeding was assumed to improve diameter and height growth by 20%. Without tree breeding effect CCF was always more profitable than clear-felling and planting. In the uneven-aged initial stand CCF was always more profitable than clear-felling and planting combined with optimal thinning, and the relative difference increased with increasing discount rate. If planted trees were assumed to grow 20% faster than natural regeneration, clear-felling was better than CCF in the old initial stand irrespective of discount rate, and the relative difference was nearly the same with all rates. Increasing discount rate increases the opportunity cost of letting the trees to continue growing, making immediate cutting more urgent and profitable compared to partial cutting. On the other hand, increasing discount rate decreases the profitability of planting, and it seems that the positive and negative effects of increasing discount rate largely canceled each other in this stand.

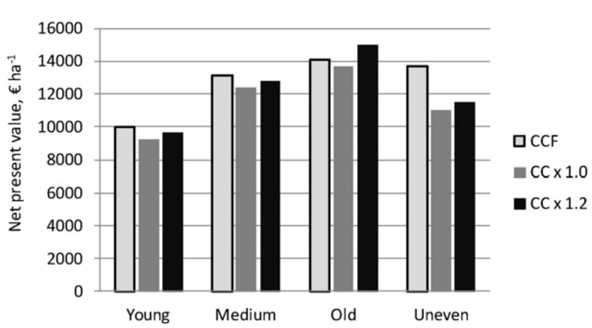

Fig. 9. NPV of optimal CCF and clearfelling (CC) schedules for four initial stands when the growth prediction of the plantation forest (seedlings planted after clearfelling) is multiplied by 1 or 1.2.

When transformation cuttings were optimized with 1 or 5% discount rate, the diameter distribution of the steady-state forest did not differ much from that obtained with 3% rate. Pre- and post-cutting stand volumes decreased with increasing discount rate, but the effect was small. When discount rate was 1%, the basal area of the pre-cutting stand ranged from 25.9 to 30.0 m^2/ha and the post-cutting basal area ranged from 10.2 to 14.5 m^2/ha. With 5% discount rate the basal area before cutting varied from 25.2 to 27.4 m^2/ha while the range of the residual basal area was 9.8–12.9 m^2/ha. Most probably the legal limit decreased the effect of discount rate on the basal area of the steady-state stand. The pre-thinning mean tree diameter was 21.6–21.7 cm and the post-thinning mean diameter was 14.2–15.8 cm when discount rate was 1%. With 5% rate the corresponding ranges were 19.0–19.8 cm for pre-cutting stand and 12.8–14.2 cm for post-cutting stand, i.e., about 2 cm smaller than with 1% rate.

4. Discussion

The results corroborate earlier findings that optimal CCF is more profitable than clear-felling and planting in Finnish spruce stands (Tahvonen, 2009; Pukkala et al., 2014a, 2014b). The only exception was a mature stand, in which clear-felling was the most profitable option when it was assumed that planted trees grow faster than natural regeneration.

The obvious reason for the superiority of clear-felling in the old stand is the high opportunity cost of mature trees. However, as suggested by Pukkala et al. (2014a), the true optimum, without considering

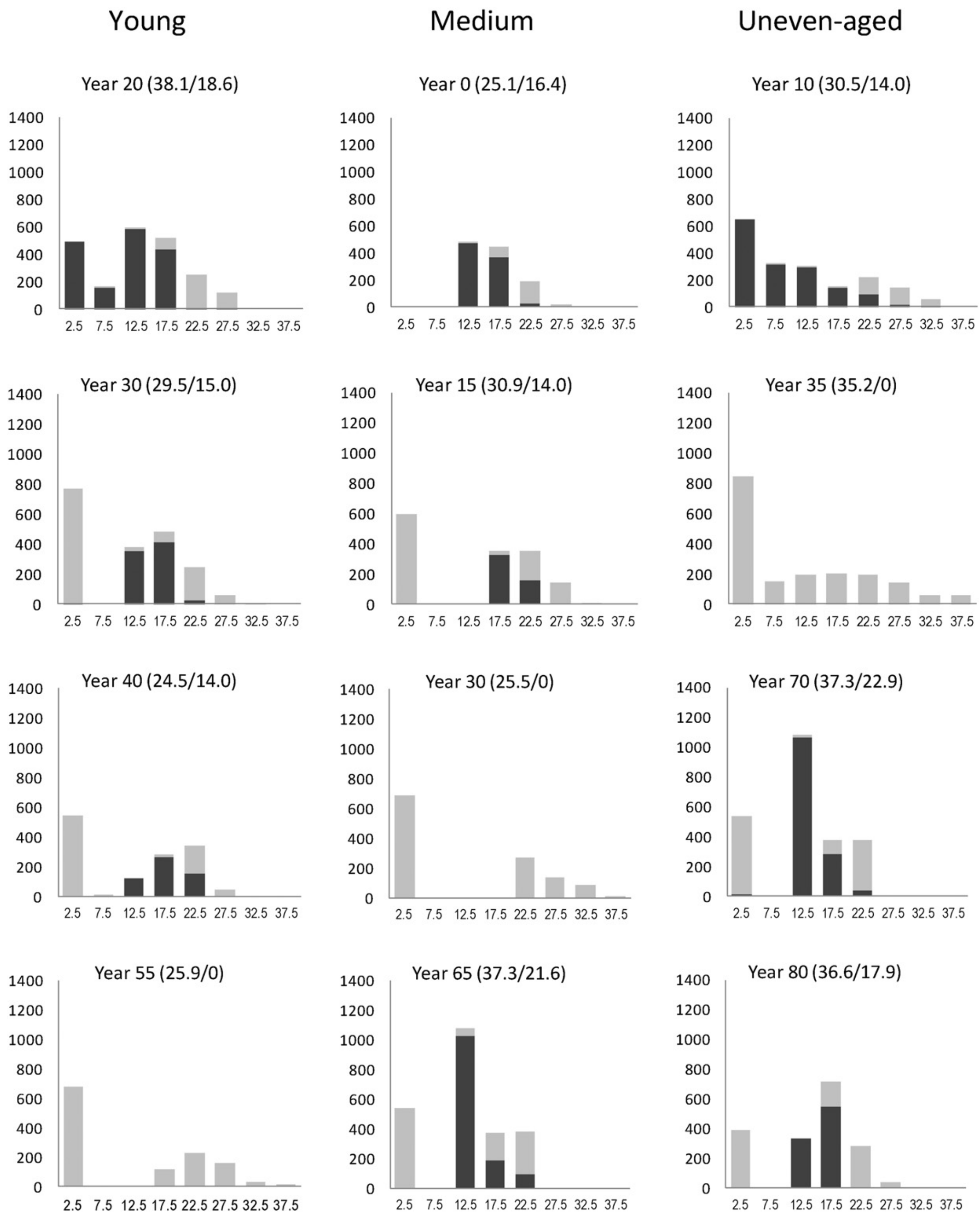

Fig. 10. Optimal timing and type of cuttings for young (left), medium-aged (middle) and uneven-aged (right) initial stand in even-aged management. Pre- and post-cutting stand basal areas (m^2 ha^{-1}) are shown in parentheses. The growth of the trees planted after clear-felling were assumed to be 20% more than the model prediction.

the legal limits, would still be a partial cutting, but to residual basal area that is lower than the legal limit. If the tree breeding benefit is not extremely high, the best way to regenerate mature even-aged stands would be natural regeneration by shelter and seed trees, or using seeding from adjacent stands. However, the legislation requires that tall enough regeneration must be obtained within a rather short time span, otherwise the stand must be regenerated artificially. Therefore, if natural regeneration is used, there is a possibility that planting becomes necessary due to legal reasons, decreasing the profitability of this management option. Since the outcome of natural regeneration is hard to predict with certainty, the best approach to including natural regeneration in the analyses would be stochastic optimization (Lohmander, 1995, 2007; Yousefpour et al., 2012; Pukkala, 2015).

The NPV-differences between CCF and even-aged management were not very high, as compared to some earlier studies (e.g. Pukkala et al., 2010). This is because calculations were started from existing stands, and high-thinnings (or "temporary CCF management") were allowed also in even-aged management. If fact, all thinnings of the

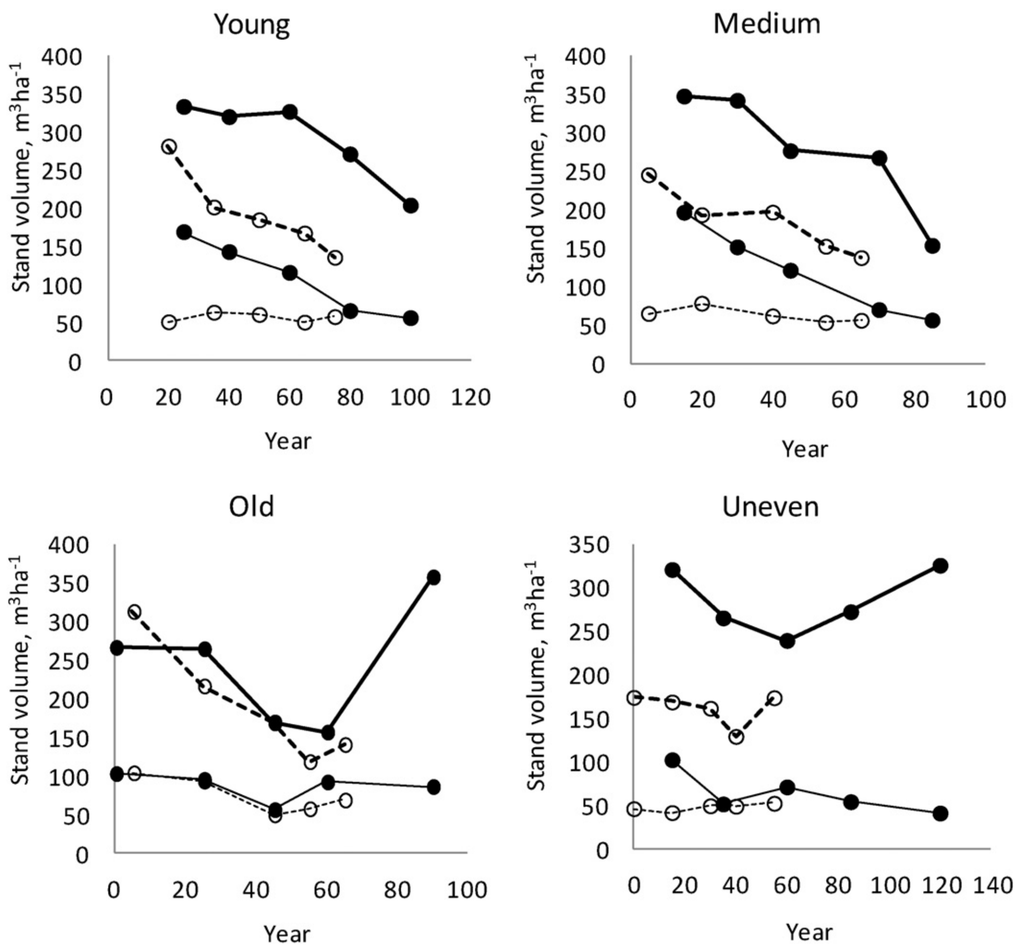

Fig. 11. Sequence of pre- and post-cutting volumes in optimal CCF with 1% (continuous lines, filled circles) and 5% (dashed lines, open circles) discount rate.

clear-felling schedules were high thinnings, suggesting that it is always optimal to continue CCF-type of management as long as sufficient size variation can be maintained in the stand. Since the emergence of advance regeneration is again a stochastic phenomenon, it may not be recommendable to give exact threshold conditions for choosing between long-term even-aged management and CCF management. However, it would be possible to develop adaptive rules that tell when a certain stand should be cut and which kind of cutting should be conducted (Gong and Yin, 2004; Pukkala, 2015). Uncertainty related to growth and timber price could also be included in these analyses.

The result that the optimal management schedules sometimes include clear-felling and planting does not mean that even-aged management is more profitable than CCF in those cases. As pointed out by Tahvonen et al. (2010) it may be optimal to clear fell a mature stand once and pursue CCF in the new tree generation. However, this depends on the development of the planted tree stand: if the size variation among planted trees remains narrow and there is little advance regeneration, it may be optimal to clear-fell the stand again if natural regeneration by shelter trees is ruled out.

The advantages of clear-felling and planting are cheaper logging and the possibility to benefit from genetically improved planting stock. In this study, the harvesting cost of clear-gelling was mostly 6.5–7 €/m^3, whereas the harvesting cost of selective high thinnings ranged from 7 to 10 €/m^3. However, in some cases the harvesting cost per cubic meter was higher in clear-felling than in thinning; this happened in the uneven-aged stand where harvesting cost was 8.2 €/m^3 in clear-felling but only 7.3 €/m^3 in thinning. The possibility to leave small trees unharvested decreases the harvesting cost of selective high thinnings. If the stand has plenty of small-sized trees, their harvesting may have a strong negative influence on the average harvesting cost per cubic meter. This may be one reason for the result that it was often optimal to cut non-commercial small trees in thinnings if the schedule included a later clear-felling.

The gain in volume production typically ranges from 10 to 25% when using genetically improved seedlings in planting (Ruotsalainen, 2014). This study assumed a 20% gain in diameter and height increment, resulting in volume gains higher than reported in literature. Despite this, clear-felling and planting was seldom more profitable than CCF. Increases in diameter or height increments cannot be unambiguously converted into volume increments because the gain depends on the timing and intensity of thinnings in relation to the competition among trees. In the early part of the rotation, the assumed 20% tree breeding effect resulted in about 45% gain in volume production as compared to the growth of natural regeneration.

The results showed that converting the stand into steady state structure and following steady-state uneven-aged management thereafter, decreased profitability compared to optimal CCF (i.e., without any requirement for steady state). However, if 4 or 5 cuttings are allowed for the conversion, the NPV of the conversion schedule is already close to that of the optimal CCF schedule. This is partly because discounting decreases the influence of distant cuttings. The first cuttings are not much affected by the steady state constraint when many cuttings are allowed for the conversion. It is also possible that optimal CCF may converge to a steady state (Tahvonen, 2011). The likelihood of the latter possibility was not analyzed in this study. However, some of the results suggested that the pre-and post-cutting stand basal area and volume may fluctuate, implying that optimal management does not necessarily converge to any steady state structure (Pukkala et al., 2012).

The steady state diameter distribution of conversion schedules depended to some degree on the initial stand when the number of transformation cuttings was restricted. However, without any limit for the number or transformation cuttings the steady state distribution would be the same for all initial stands (Haight, 1985; Tahvonen, 2011).

Similarly to Chang (1981) and Sánchez Orois et al. (2004), declining discount rate increased both cutting interval and optimal level of growing stock. Knoke and Plusczyk (2001) found that transformation from even-aged management to uneven-aged stand structures was more profitable than continuing even-aged management when discount rate was 2% or higher. In the current study, optimal transformation schedules and optimal CCF were both more profitable than even-aged management, except in the mature even-aged stand when tree-breeding was assumed to improve the growth of planted trees.

Gove et al. (2008) noted that the diameter distributions of managed uneven-aged stands often resemble the Blurr distribution with a slight "hump" in the mid-diameter range. The optimal diameter distributions obtained in this study showed similar features: optimal pre-thinning structures had a preponderance of trees in diameter class 20–25 cm, and optimal post-cutting stand had more trees in diameter class 15–20 cm, as compare to reversed J, negative exponential distribution or a constant ratio between the frequencies of adjacent diameter classes (see also Tahvonen, 2011; Schütz et al., 2012).

The recent trends of Finnish forest management include increased use of thinning from above, lower remaining basal area in thinning treatments, increased utilization of advance regeneration, and higher flexibility and freedom in forest management. The results of this study support the conclusion that the ongoing changes increase the profitability of forest management. Regeneration by clear-felling and planting can be recommended only in mature spruce stands when genetically improved planting stock is available.

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