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Uneven- *vs* even-aged management in Finnish boreal forests

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Summary

The article summarizes results obtained from several field experiments, measured in uneven-aged forests during a long period; from the 1930s until the present. Experiments have been established in both Norway spruce- and Scots pine-dominated stands. The purpose is to evaluate the feasibility of uneven-aged forest management under Finnish conditions and compare uneven-aged management to the current even-aged forestry. The analysed datasets demonstrate relatively rich regeneration under many types of tree canopies. The number of stabilized (height 0.1–1.3 m) spruce seedlings does not always correlate with the stand density. The amount of small labile (height < 0.1 m) spruce seedlings may even increase with increasing stand volume. Contrary to spruce, the regeneration of birch and pine decreases with increasing stand volume. The yield comparisons show that uneven-aged stands have often grown faster than even-aged stands with the same post-cutting stand density. High thinnings have resulted in better volume increments than low thinnings. Recent studies show that uneven-aged management is more profitable than even-aged rotation forestry (RF), especially with high discount rates. Uneven-aged management seems to be superior to current even-aged RF also with respect to environmental and multifunctional aspects, such as carbon sequestration, bilberry yield, structural diversity and scenic values.

Introduction

In the boreal zone of Europe, forests develop into uneven-sized spatially irregular stands (Keto-Tokoi and Kuuluvainen, 2010). The National Forest Inventories (NFI) have shown that, in the early 1920s, two-thirds of Finland's forests were still either unlogged or showed only small traces of intervention (Heikinheimo, 1924). Those forests, representing quite well the whole European boreal zone, were uneven aged and uneven sized (Lähde *et al.*, 1991). Uneven-aged stands were prevailing among mature stands also in later inventories conducted during the 1950s and 1990s (Lähde *et al.*, 1992b; Pukkala *et al.*, 2011b). Forest inventory data in the other Nordic Countries have indicated that uneven-aged forests have predominated also there (e.g. Uppskattning av Sveriges skogstillgångar verkställt åren, 1923–1929, 1932; Nilsson and Östlin, 1961; Skogsstatistisk årsbok, 1989).

Comparative field trials of uneven- and even-aged management were not established in Finland until the 1980s (Lähde *et al.*, 1992a), despite repeated debates concerning uneven-aged management and increasing interest of the public to find alternatives for the prevailing rotation forestry (RF) based on clearfelling and planting (Siiskonen, 2007). The declaration against uneven-aged management (Appelroth *et al.*, 1948) contributed to the cessation of uneven-aged management and other variants of continuous cover forestry (CCF). This declaration, which strongly affected forest management in Finland for several decades, was not based on any systematic comparison of alternative silvicultural methods. One argument used against uneven-aged management was that the shade tolerance and regeneration of Finnish tree species are insufficient. However, the aforementioned NFI data confirm that shade intolerance did not prevent Finnish forests from regenerating and developing into uneven-aged stands.

This article reviews several Finnish datasets and studies on uneven-aged forests. Some of them are analysed in new ways, leading to new results and conclusions. Thus, the article is partly a review of earlier research but it also presents new results. The purpose is to evaluate the possibilities to practice CCF in Finnish conditions. The main topics discussed are the regeneration capability of Finnish tree species under the canopies of mature trees and the yield and profitability of CCF as compared with those of even-aged RF.

Regeneration of uneven-aged forests is examined in the next section. The third section compares the yields of uneven-aged stands to those of even-aged forests. Next, the economic profitability of different management systems is discussed. The last sections of the article deal with harvesting issues as well as some environmental and multifunctional aspects of uneven- and even-aged forests.

Regeneration of uneven-aged forests

Sarvas' data

An old dataset collected by Sarvas (1944) contains information about the regeneration of uneven-aged forests in southern Finland. The 195 research plots were established in Norway spruce-dominated (*Picea abies* (L.) Karst) and Scots pine (*Pinus sylvestris* L.)-dominated forest stands treated with selective cuttings during the 1920s and 1930s. The plots were measured at the end of the 1930s. Sarvas (1944) excluded 18 per cent of the plots in his study. This article analyses all the plots. The data used in this study are referred to as the augmented Sarvas dataset.

The plots measured in spruce-dominated uneven-aged stands had a rich regeneration of Norway spruce and birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.), and pine-dominated stands had plenty of Scots pine and Norway spruce seedlings (Table 1). The so-called labile seedlings (height < 0.1 m) of spruce numbered many thousands per hectare and their amount slightly increased with stand density (Figure 1). In contrast, the number of labile Scots pine and birch seedlings decreased with increasing stand density. The so-called stable or stabilized (height 0.1–1.3 m) spruce seedlings did not diminish with increasing s tand density indicating good shade tolerance of the seedlings.

The stabilized seedlings of the main tree species, Scots pine, Norway spruce and birch, together numbered, on average, close to 5000 ha^{-1}. Their amount was almost twice more in spruce-dominated stands (6800 ha^{-1}) than in pine-dominated ones (3600). The number of stabilized spruce seedlings was higher in spruce-dominated stands (5600 ha^{-1}) than in pine-dominated ones (1700). The number of pine seedlings was the highest in the sparsest (<50 m^3 ha^{-1}) pine-dominated stands (2200 ha^{-1}). The number of birch seedlings varied very much decreasing with increasing stand volume. More than half of the dense plots did not have birch or pine seedlings at all.

Other datasets

An NFI dataset collected about 30 years later, during the 1950s, confirms the rich regeneration indicated by the Sarvas' data (Table 2). However, only large stabilized seedlings (conifers > 20 cm and birches > 50 cm in height) were recorded. The seedlings of the main tree species numbered ~1300 ha^{-1} in the pine-dominated stands and slightly less in spruce-dominated stands. Their amounts were the highest when the stand volume was low (Table 2).

In later field trials, established during the 1980s and measured in 1990 (Lähde *et al.*, 1992a,b), regeneration has been studied in both untreated and recently treated uneven-aged spruce-dominated stands (Table 3). The experiments summarized in Table 3 contain 63 plots. Again, the results indicate large amounts of both labile and stabilized seedlings. The labile spruce seedlings numbered tens of thousands per hectare being the most abundant in dense stands. The number of stabilized spruce seedlings was also high, some thousands per hectare, but there was no clear correlation with the stand volume. There were many birch seedlings, ~5000 ha^{-1}, in volume class less than 100 m^3 ha^{-1}. Variation among the plots was large. The number of pine seedlings was very low. The amounts of labile and stabilized birch and pine seedlings decreased when the stand volume increased.

Two other silvicultural trials (Lähde *et al.*, 1999a) comparing uneven- and even-aged management were established in Central Finland (in Vessari and Honkamäki) in 1986/1987. These two management systems had altogether 47 uneven-aged plots. Regeneration of the main tree species, mostly spruce, was high in the lowest stand volume classes. However, because of long period of over-stocking, regeneration was low in the densest stands (Table 4). In this material, contrary to earlier research, the negative correlation between the number of seedlings and the stand volume was clear.

More recently, Saksa (2004), Valkonen and Maguire (2005), Eerikäinen *et al.* (2007) and Saksa and Valkonen (2011) have analysed the regeneration in Norway spruce-dominated stands in southern Finland treated with uneven-aged management during the 1990s. In the latest study (Saksa and Valkonen, 2011), the number of labile spruce seedlings was many thousands per hectare. There were, on average, also some thousands stabilized spruce seedlings per hectare when the stand-basal area varied between 15 and 33 m^2 ha^{-1}. However, variation between plots was high. In Saksa's (2004) data, measured 5 years earlier, the average number of stabilized spruce seedlings was several thousands per hectare when the basal area varied between 10 and 25 m^2 ha^{-1}. Pukkala *et al.* (2011b) calculated the number of seedlings in the permanent sample plots established in the 8th NFI in 1985. The number of stabilized pine, spruce and birch seedlings was at least 1000 ha^{-1} in 80 per cent of the NFI plots.

Because of high stand basal areas and many competing larger understorey trees present in most uneven-aged stands (see Tables 1–4), the height increment of the seedlings has been rather slow (e.g. Lundqvist, 1989; Lähde, 1992a,b; Saksa and Valkonen, 2011).Therefore, it would take even 30–60 years until all spruce seedlings reach the breast height (Lundqvist, 1989; Saksa and Valkonen, 2011). Most stands in which height growth has been measured represent stand basal areas clearly higher than the optimal ones found

Table 1: Growing stock and seedling data in selectively cut pine- and spruce-dominated stands by volume classes in southern Finland in 1930s in the augmented Sarvas dataset

	Pine-dominated			Spruce-dominated		
	Volume class, m^3 ha^{-1}					
	<50	50–100	>100	<50	50–100	>100
Number of plots	65	31	16	37	31	15
Volume, m^3 ha^{-1}	27	72	145	31	67	135
Growth, m^3 ha^{-1} a^{-1}	1.6	3.2	4.2	2.5	4.3	5.9
Growth, %	6.3	4.5	3.1	8.1	6.5	4.4
No of stems per hectare by diameter class						
d.b.h. >20 cm	38	82	157	37	82	155
d.b.h. 10–20 cm	101	335	539	116	272	483
d.b.h. 1–10 cm	1268	1589	438	2357	2227	2446
Stabilized seedlings (0.1–1.3 m) ha^{-1}						
Pine	2244	1250	579	429	166	119
Spruce	1659	1830	1436	6766	3411	7337
Birches	223	79	66	1043	846	451
Total	4127	3159	2080	8238	4423	7908
Labile seedlings (<0.1 m) ha^{-1}						
Pine	854	565	313	189	129	167
Spruce	877	1226	21000	1878	2435	5300
Birches	331	32	0	514	1790	33
Total	2062	1823	21313	2581	4355	5500

d.b.h, diameter at breast height.

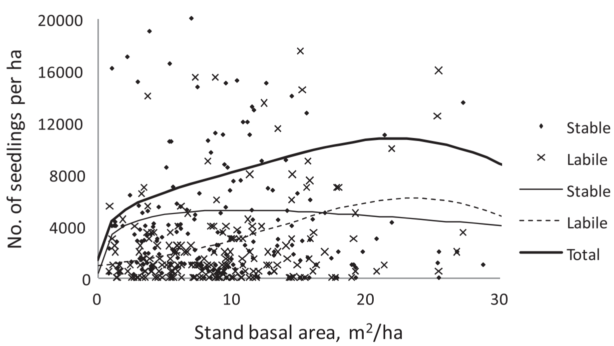

Figure 1. Number of stable and labile seedlings in the dataset of Sarvas (1944). The thin lines are models fitted to the data between stand basal area and number of seedlings. The 'Total' line is the sum of the predictions of the models for stable and labile seedlings. Note that the *y*-axis is cut at 20 000 (there were frequently more than 20 000 labile seedlings per hectare).

by Pukkala *et al.* (2010). On the other hand, an equal and fast height development of all seedlings is not as necessary as in even-aged stands. For the sustainability of uneven-aged structure, only two or three hundreds of the seedlings per hectare need to grow fairly rapidly (Lähde, 1992a).

Yield comparisons between uneven- and even-aged forests

The aforementioned Sarvas' (1944) dataset also contained information about the growth of uneven-aged stands treated with heavy selective cuttings (Table 1). As shown in Figure 2, the measured annual volume increments of selectively cut stands represent typical values for different sites, similar as can be expected in even-aged stands. Despite this, the studies of Sarvas and especially his results on volume increment have been used as an argument against uneven-aged management. The low mean volume increment has been interpreted to indicate poor performance of uneven-aged stands in Finland. However, in half of the Sarvas' plots, the stand volume was less than 50 m^3 ha^{-1} (Table 1) and the mean volume was only 29 m^3 ha^{-1}. Therefore, the average volume growth of the total material was rather low, 3.0 m^3 ha^{-1} a^{-1}, although the growth of denser plots appears to be quite normal according to Figure 2.

Sixteen per cent of Sarvas' plots had a growing stock volume of over 100 m^3 ha^{-1}. The diameter distributions of these stands (Table 1) resembled the uneven-aged stand structure (cf. Lähde *et al.*, 1991). Their annual volume growth was 4.2 m^3 ha^{-1} in the pine-dominated stands and 5.9 m^3 ha^{-1} in the spruce-dominated ones. These are typical values for even-aged stands growing on corresponding sites. The annual volume growths are higher than the average values for advanced thinning forests (3.7 m^3 ha^{-1} a^{-1} for pine-dominated stands and 5.3 m^3 ha^{-1} a^{-1} for spruce-dominated stands) in the same region at that moment (Ilvessalo, 1956).

During the 1980s, various experiments were established in Finland which contained plots representing both uneven- and even-aged management in similar conditions (Lähde *et al.*, 1992a). One dataset consists of two experimental fields (Vessari and Honkamäki) with randomized

Table 2: Growing stock and seedling data for uneven-aged pine- and spruce-dominated stands by volume classes in southern Finland according to the third NFI in 1951–1953

	Pine-dominated			Spruce-dominated		
	Volume class, m^3 ha^{-1}					
	<50	50–100	>100	<50	50–100	>100
Number of plots	39	285	252	31	398	658
Volume, m^3 ha^{-1}	44	75	142	44	78	152
No of stems per hectare by diameter class						
d.b.h. >20 cm	35	67	151	38	79	181
d.b.h. 10–20 cm	298	407	558	248	390	516
d.b.h. 1–10 cm	1879	2605	3227	1903	2561	3183
Stabilized seedlings per hectare						
Pine (0.2–1.3 m)	937	491	319	106	149	87
Spruce (0.2–1.3 m)	638	550	647	819	740	775
Birches (0.5–1.3 m)	198	242	184	419	294	209
Total	1773	1283	1150	1344	1183	1071

d.b.h., diameter at breast height.

Table 3: Growing stock and regeneration data in advanced uneven-aged spruce-dominated experimental stands by volume classes in southern Finland.

	Volume class, m^3 ha^{-1}		
	<100	100–200	>200
No of plots	9	32	22
Volume, m^3 ha^{-1}	86	142	245
Growth, m^3 ha^{-1} a^{-1}	4.5	5.6	5.7
Growth, %	5.5	3.9	2.4
Stabilized seedlings (0.1–1.3 m) ha^{-1}			
Pine	188	12	9
Spruce	6543	2767	4013
Birches	4849	2775	523
Total	11589	5554	4544
Labile seedlings (<0.1 m) ha^{-1}			
Pine	417	107	14
Spruce	48500	73313	125511
Birches	3611	2746	355
Total	52527	76166	125880

Table 4: Growing stock characteristics and regeneration data of main tree species (pine, spruce and birches) in uneven-aged spruce-dominated experimental stands by volume classes in southern Finland

	Volume class, m^3 ha^{-1}		
	<100	100–200	>200
No of plots	7	19	21
Volume, m^3 ha^{-1} in 1996	73	170	286
Growth, m^3 ha^{-1} a^{-1}	6.8	7.0	7.4
Growth, %	8.4	4.4	2.6
No of stems per hectare by diameter class			
d.b.h. >20 cm	33	144	205
d.b.h. 10–20 cm	429	719	1244
d.b.h. 1–10 cm	2586	1989	3468
Stabilized seedlings (0.1–1.3 m) per hectare			
In 1996	11357	4005	1071
In 2004	11629	5016	733
In 2006	10700	4426	700
Height increment (cm/a) of spruce seedlings in 2004–2006			
All seedlings	2.5	2.2	1.6
300 fastest ha^{-1}	4.7	3.7	2.0
100 fastest ha^{-1}	5.2	4.5	2.4

Thinnings have been conducted in 1986–1987, 1994 and 2002.
d.b.h., diameter at breast height.

plots of uneven- and even-aged management. The experiments were established in stands naturally regenerated during the 1940s. Thus, the even-aged plots had already reached the end of the rotation (75 years) by 2010. According to the long-term measurements of the remaining, removed and dead trees, the yield of uneven-aged management (6.6 m^3 ha^{-1} a^{-1} in Vessari and 5.6 m^3 ha^{-1} a^{-1} in Honkamäki) has been better than in the plots treated with low thinning and even-aged management (6.4 and 5.0 m^3 ha^{-1} a^{-1}). However, the differences are not statistically significant due to large between-plot variation. When only those uneven-aged plots of Vessari are examined that have already reached the targeted diameter distribution, the growth is higher, 7.4 m^3 ha^{-1} a^{-1} (Lähde *et al.*, 2010).

Several pairs of plots covering the whole country and treated at random with uneven- and even-aged management were established also during the 1980s and followed for one 10-year thinning cycle (Lähde *et al.*, 2002). The annual growth of the uneven-aged plots treated with high thinning (5.4 m^3 ha^{-1}) was 17 per cent higher than in the even-aged plots treated with low thinning. If small trees (diameter growth at breast height < 9 cm) are included in the analysis (they were excluded in Lähde *et al.*, 2002), the growth of uneven-aged plots (5.9 m^3 ha^{-1} a^{-1}) was 31 per cent higher than in the even-aged plots. The difference is statistically highly significant (Figure 3). The data of the third NFI also suggest that uneven-sized stand structures may have

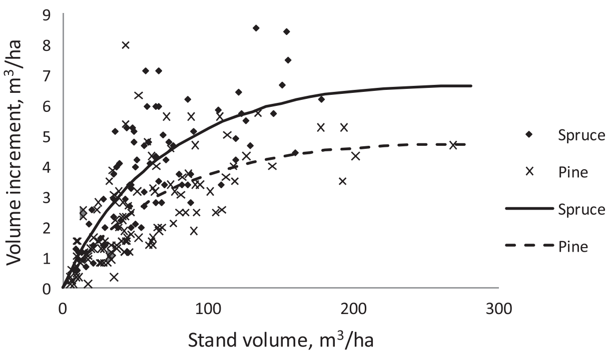

Figure 2. Annual volume increment in pine- and spruce-dominated stands in the augmented Sarvas (1944) data. The lines represent a model fitted to the data, expressing the increment as a function of stand volume and dominant tree species.

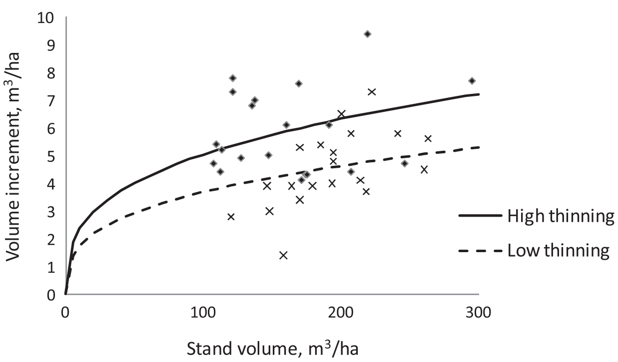

Figure 3. Post-thinning volume increment in stands treated with high (squares, solid line) and low thinning (Lähde *et al*., 2002). The lines represent a model fitted to the data. The effect of thinning type (high/low) is highly significant.

better volume increments than even-aged and even-sized stands when the stand volumes are at the same level and not very low (Table 5, cf. also Lähde *et al*., 1994a,b). The growth differences between even- and uneven-aged management are significant for relative growth but not for absolute growth. Similar results based on other datasets have been obtained by Lähde *et al.* (2001).

Similar results have been obtained also in the other Nordic countries. For instance, the data of Lundqvist and Nilson (2007) indicate a very clear and significant superiority of high thinning and uneven-sized post-cutting stands as compared with low thinnings corresponding to the prevailing even-aged management. Encouraged by successful trials, a large private forest holding in Glommen, north of Oslo, recently switched to CCF in both pine and spruce forests (e.g. Ökseter and Myrbakken, 2005). Eikenes *et al.* (1996) in Norway found that also the wood quality of uneven-aged forest is better than that in planted forest.

Profitability of uneven- and even-aged management

The net present value (NPV) on even-aged plantation forestry usually goes negative at 3–5 per cent interest rates depending on the growth conditions and timber prices (e.g. Hyytiäinen and Tahvonen, 2003). On the other hand, it can be concluded that the NPV of the optimal uneven-aged management is always positive. If the stand is thinned only when it gives positive cash flow, no other management actions are taken, and only non-merchantable trees are left in the residual stand, the NPV is positive also with very high rates of interest. A positive NPV irrespective of discounting rate is also achieved when a clear-cut area is allowed to regenerate naturally without site treatments and sapling management.

In the aforementioned long-term comparative field experiments of Vessari and Honkamäki, the NPV, when all net incomes were discounted with 3 per cent rate to the starting year of the experiment (1986/1987), was 20 per cent greater for uneven-aged management (CCF) than for even-aged RF (Pukkala *et al*., 2011b). Uneven-aged management mainly logged saw log-sized trees, which have a low relative value increment, often below the market interest rate. This results in better profitability than thinning from below, which removes small trees having low opportunity cost but high relative value increment (Tahvonen, 2009; Pukkala *et al*., 2009, 2010; Tahvonen *et al*., 2010).

These results agree with those of Pukkala *et al.* (2010), who found that CCF is more profitable than RF with all discounting rates in all forest types except the best spruce sites of South Finland with 1 per cent rate. The results of Tahvonen *et al.* (2010) also confirm the good profitability of uneven-aged management. The relative superiority of CCF management improves with increasing discount rate (Figure 4) and management costs and with decreasing site productivity and timber price (Tahvonen, 2009).

In Sweden, Wikström (2000) obtained higher NPVs for RF than for CCF. However, Wikström (2001) himself admits that his results cannot be used to compare the profitability of RF and CCF because the growth of uneven-aged stands was underestimated and ingrowth was an arbitrarily set constant. In addition, calculations were done for financially mature stands for which immediate regeneration would have been optimal. However, this treatment was prevented by the constraints of the optimization problems. As a result, the uneven-aged stands were constantly too old and dense.

Andreassen and Øyen (2001) found clearfelling and planting to be more profitable than selective cutting in financially mature spruce stands in Norway. Similarly to Wikström (2000), the optimal CCF alternative, i.e. immediate natural regeneration followed by normal uneven-aged management, was not included in the analysis. In addition, the growth predictions were multiplied by 0.85 in CCF. Therefore, these Swedish and Norwegian studies only show that financially mature stands should not be treated with repeated light thinnings; instead, they should be rejuvenated by using relatively heavy regenerative cuttings.

Table 5: Growing stock characteristics of pine- and spruce-dominated stands by stand structure in southern Finland according to the third NFI in 1951–1953

	Pine-dominated		Spruce-dominated	
	Uneven-aged	Even-aged	Uneven-aged	Even-aged
No of plots	1200	412	2252	571
Volume, m^3 ha^{-1}	93	118	116	152
Growth, m^3 ha^{-1} a^{-1}	3.8	3.6	5.5	5.5
Growth, %	4.3	3.2	5.1	3.9
No of stems ha^{-1}				
d.b.h. >20 cm	99	166	147	217
d.b.h. 10-20 cm	481	458	559	618
d.b.h. 2–10 cm	1733	208	1871	259

The difference in relative growth between even- and uneven-aged stands is highly significant. d.b.h., diameter at breast height.

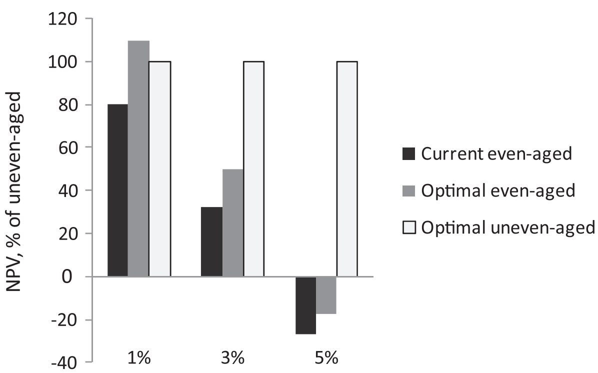

Figure 4. Relative net present value (uneven aged = 100) of a mesic spruce site in southern Finland in currently practiced even-aged plantation forestry based on low thinning, optimal plantation (even-aged) forestry using high thinning and optimal uneven-aged forestry. The analysis is based on growth simulations that use the models of Hynynen *et al.* (2002) for even-aged stands and Pukkala *et al.* (2009) for uneven-aged stands.

Harvesting issues in the uneven- and even-aged managements

There have been some comparative studies on the logging and harvesting costs of different management methods (Imponen *et al.*, 2003). These show that clear-cutting is the cheapest harvesting method. It is, however, only one of the several cuttings during the rotation of the even-aged management. Thinnings, especially the first commercial thinning, are expensive. As a result, Imponen *et al.* (2003) concluded that, over a period corresponding to the whole even-aged rotation, the average harvesting costs of CCF are not higher than those in even-aged forestry.

Harvesting costs can be estimated with models instead of field trials. For example, Rummukainen *et al.* (1995) developed a model for the time needed to cut and limb a tree and another model for the forwarding time. If the forwarding distance is 100 m and the terrain easy, the models predict that the cost of logging and harvesting is more expensive per harvested cubic meter in uneven-aged management (9 €/m^3) than in the clearfelling of RF (6 €/m^3). However, harvesting is cheaper than in the first (15 €/m^3) and second (10 €/m^3) commercial thinning of an even-aged forest.

There is an increased risk of root and butt rot infection by *Heterobasidion* when harvesting during summer. If an infected spruce stand is regenerated with spruce, the disease will spread also to the next tree generation (e.g. Möykkynen and Pukkala, 2009). Therefore, clearfelling and planting with spruce does not make the stand healthy again. Irrespective of management system, a badly infected stand should be primarily regenerated for deciduous tree species.

Environmental and multifunctional aspects

The long-term carbon balance of uneven-aged management seems to be slightly better than that of even-aged one (Pukkala *et al.*, 2011a). Especially in spruce stands, the carbon balance is maximized by minimizing the harvesting of pulpwood-sized trees, since – unlike sawn wood and biofuel – spruce pulpwood has no substitution effects. Production of mechanical pulp from spruce also consumes much energy.

The models by Miina *et al.* (2009) indicate that a mesic spruce forest gives its greatest blueberry yield when the basal area is 15–20 m^2 ha^{-1}. In the optimal CCF, the basal area is maintained at this level for most of the time (Pukkala *et al.*, 2011b). According to Miina's model, the long-term blueberry yield of an uneven-aged stand is three times that of an even-aged one (Figure 5).

According to Silvennoinen *et al.* (2001), Finns perceive multi-layered stands with a sparse layer of large trees and coniferous understorey as the most beautiful. The tree diameter distribution should be positively skewed resembling an inverted J. Large pines and birches improve the scenic value. The long-term average of the 'scenic beauty index' developed by Silvennoinen *et al.* (2001) is clearly better in uneven-aged stands than in the current even-aged ones (Figure 6).

Clear-cutting changes the environment of many species for decades. The species diversity of a forest stand is greatest when the stand contains many structural elements, such as tree species, canopy layers and various types of decaying wood. The mean long-term structural diversity index developed by Lähde *et al.* (1999b) is better in uneven-aged stand as compared with the current even-aged management (Figure 6).

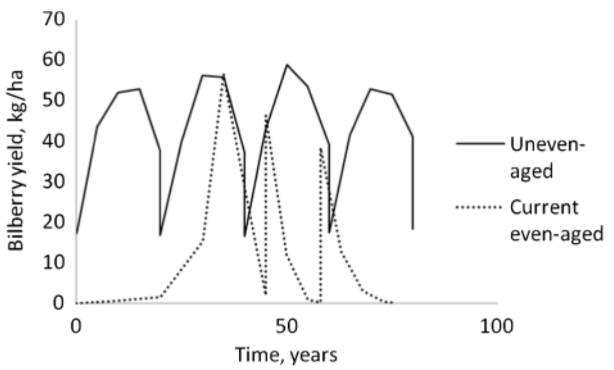

Figure 5. Predicted bilberry yield during one rotation of current even-aged management on a mesic spruce site in Central Finland and the yield in uneven-aged forestry with a 20-year cutting cycle.

Conclusions

The boreal forests of Europe often develop into mixed multi-layered or uneven-aged stands. Even-aged stands are obtained after the most severe disturbances and clearfellings. However, disturbances that destroy all trees are rare (e.g. Keto-Tokoi and Kuuluvainen, 2010). In addition, the even-aged stage following a major disturbance is temporary representing only a small fraction of the whole succession of stand stages in natural forest dynamics.

Old and new forest inventory data show that natural regeneration is abundant in most forests. This suggests that management systems relying on continuous natural regeneration are feasible in Finnish forest conditions. In the case of local deficiencies in regeneration, stronger cuttings enhancing the regeneration of pioneer species may be used. Planting is also an option, especially if the landowner wants to have regeneration of a certain tree species.

Of the Finnish tree species, Norway spruce is the most shade tolerant. The datasets analysed in this article indicate that spruce may regenerate also under dense canopies. The amount of spruce 1-year-old seedlings appears to depend more of seed crops and germination conditions (moisture) than the characteristics of the overstorey trees. However, pure and dense spruce stands without any admixture of hardwood and pine may have very little regeneration. A strong cutting is required in these stands to encourage

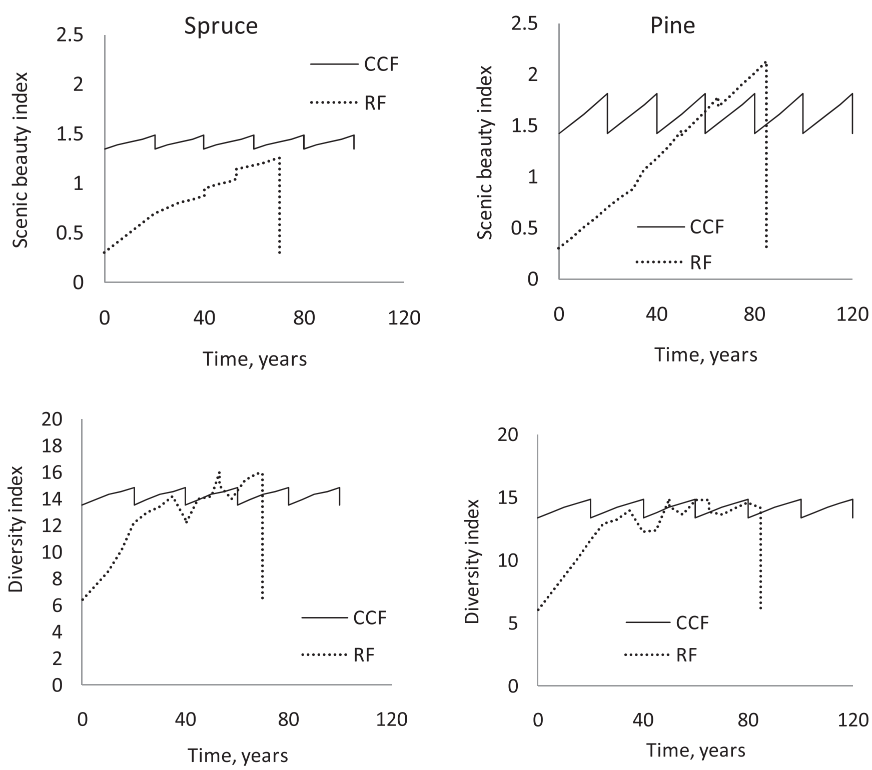

Figure 6. Development of a scenic beauty index (Silvennoinen *et al.*, 2001) and a structural diversity index (Lähde *et al.*, 1999b) in optimal steady-state uneven-aged management (CCF) and optimal rotation (even-aged) forestry (RF).

regeneration. Maintaining the stand as a mixed stand would also benefit regeneration. Stronger cuttings are also necessary for improving the height growth of seedlings. The stand-basal areas of optimal uneven-aged management systems, 10–20 m^2 ha^{-1} (Pukkala *et al.*, 2010), would most probably be good for regeneration and height development of the seedlings.

Regeneration has been measured also in Sweden and Norway, mainly in uneven-aged Norway spruce-dominated forests (e.g. Böhmer, 1957; Nilsen, 1988; Lundqvist, 1989, 1991, 1995; Lundqvist and Fridman, 1996; Nilson and Lundqvist, 2001; Hanssen, 2002; Hanssen, 2003; Hanssen *et al.*, 2003; Chrimes and Nilson, 2005). The results have been rather similar as in Finland, often with thousands of Norway spruce seedlings per hectare.

The analysed NFI datasets and comparative experiments established during the 1980s suggest that uneven-aged stands may grow better than even-aged forests in terms of stem volume. Another result is that high thinning leads to better volume increment than low thinning. With post-cutting stand volume of ~150 m^3 ha^{-1}, the volume increment of spruce-dominated forests has been 5.2–7.4 m^3 ha^{-1} a^{-1} in uneven-aged stands and 4.5–6.4 m^3 ha^{-1} a^{-1} in even-aged stands. In addition, repeated high thinnings in uneven-aged stands appear to gradually increase the growth rate (Lähde *et al.*, 2010). According to Finnish datasets, cutting the stand into a remaining growing stock volume of ~100 m^3 ha^{-1}, which is the optimal residual volume in economically optimal uneven-aged management, does not decrease volume increment much compared with higher stand densities (Figures 2 and 3).

Long-term productivity studies combined with economic calculations have indicated that the profitability of the current practices based on clear-cutting, planting and low thinning is poor. It gets further weaker with poorer sites and lower timber prices and with higher discount rates and costs (e.g. Tahvonen, 2009). In addition, the current forestry practices have poor carbon balance, negative landscape impacts and unfavourable ecological consequences. Moreover, clearfelling is against people's comprehension about good forest management (Valkeapää *et al.*, 2009).

Sometimes, uneven-aged management and CCF in general have been claimed to be suitable only for old pure spruce stands with a stand diameter distribution perfectly matching a reversed J (e.g. Lundqvist *et al.*, 2009; Valkonen *et al.*, 2010). However, CCF can be practiced also in many other stands. Birch and pine stands with a spruce understorey are examples of easy places to initiate CCF. According to NFIs, such stands are very common in Finland (Pukkala *et al.*, 2011b).

Research should more actively seek alternatives to the current widely used but increasingly criticized clear-cut-based approach. Management systems other than even-aged management should be studied and practiced more, for instance, possibilities to relay on natural regeneration also in clearfelling areas. It can be calculated (Pukkala *et al.*, 2011b) that, as the site weakens and interest rate increases, it is profitable to give up site preparation and artificial regeneration also in clearfelling areas. Such extensive regeneration alternatives should be primarily considered in the boreal forests, especially on peat lands and on poor soil types.

The productivity of a stand – when it is not too sparse – is determined mostly by the site and the tree species. This means that large differences in long-term timber yields between different management methods are unlikely. Other factors than yield will therefore determine which methods should be used. Moreover, maximizing timber yield does not generally maximize economic profitability. Profitability is good when large trees with low relative value increment are logged instead of small trees with high relative value increment. Logging should be conducted in such a way that the stumpage value of the growing stock is greatly reduced while simultaneously reducing the value increment as little as possible. Another key to profitability in the boreal slow growing forests is cost minimization. This means extensive management with minimal silviculture instead of the currently recommended intensive management with far too many silvicultural operations.

Conflict of interest statement

None declared.

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