

# Optimizing the structure and management of uneven-sized stands of Finland

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## Summary

In Finland, uneven-sized forest management is gradually becoming an acceptable practice. At the moment, there are no silvicultural instructions for the management of uneven-sized forests, although there is willingness among forest owners to adopt this practice. This study optimized the steady-state structure and management of uneven-sized Scots pine and Norway spruce stands, so as to help develop management instructions. The post-thinning diameter distribution of the uneven-sized stand was optimized with 20-year cutting cycle when aiming at maximal economic profitability. Spruce stand optimizations were done for fertile and medium sites and pine stand optimizations for medium and poor sites. The optimal post-thinning distributions had a truncated reverse J shape, the frequencies of all trees larger than 18–20 cm being zero. This shape means that all log-sized trees have to be removed at 20-year intervals when economic profitability is maximized. When sawlog production was maximized, the largest retained trees were 25–30 cm in diameter at breast height (d.b.h.). The optimal diameter distributions of pine stands were clearly more uniform than spruce distributions, i.e. the preponderance of small trees was less pronounced in pine. With 2 per cent discounting rate, the optimal post-thinning basal area of trees larger than 5 cm d.b.h. was 11–12 m<sup>2</sup> ha<sup>-1</sup> for fertile spruce stands and 4–9 m<sup>2</sup> ha<sup>-1</sup> for pine stands and spruce stands of medium fertility. Uneven-sized management was found to be more profitable than even-aged management; even-aged management was more profitable only in spruce stands on fertile sites in southern Finland with low discounting rate (1 per cent). Increasing discounting rate and decreasing site productivity improved the relative performance of uneven-sized management.

## Introduction

The form and width of the diameter distribution of trees are the most commonly used characteristics in the classification of stand structure. Stands having more small trees than large ones are called uneven aged or uneven sized (Daniel *et al.*, 1979). Their diameter distribution is a descending curve, which, however, may have small peaks in larger diameter classes (Westphal *et al.*, 2006). According to the national forest resource inventories, this kind of stand structure was the dominant stand structure in the 1900s in both Sweden (Uppskattning av Sveriges skogstillgångar verkställt åren 1923–1929, 1932; Nilsson and Östlin, 1961; Skogsstatistisk årsbok, 1989) and Finland (Lähde *et al.*, 1991, 1992, 1999). Many field experiments and other observations suggest that the natural dynamics of boreal forests result in uneven-sized stands (Huse, 1965; Pobedinski, 1988; Zackrisson *et al.*, 1995; Rouvinen and Kuuluvainen, 2005).

The continuity of uneven-sized stand structure lies in certain key characteristics. Survival and revival of the understorey trees as well as the amount and composition of regeneration largely determine the dynamics, potential and

internal heterogeneity of the stand. Regeneration and establishment of seedlings and their further transition into larger diameter classes have to fill the gaps left through the removal of larger trees. Suitable cutting interval and intensity depend on the rapidity of the regeneration and ingrowth processes. However, all understorey trees do not need to revive simultaneously and grow at the same rate. Regeneration is seldom a continuous process in boreal forests due to large temporal variations in seed crops and germination conditions (Lähde *et al.*, 1999). Therefore, variation in understorey growth rate helps to compensate for the pulses of regeneration and maintain continuous ingrowth.

Although uneven-sized stand structures have been common in boreal forests, there are no official instructions for this management system. On the contrary, uneven-sized management has even been banned in Finland since the 1950s (Siiskonen, 2007) even though uneven-sized stands have been found to have higher volume increments than even-sized stands (Lähde *et al.*, 2002, 2009). The Finnish Forest Law sets strict limits for the regeneration and thinning of even-sized management. Depending on the location,

stage of stand development and site type, a certain amount of growing stock has to be left after thinning an even-sized forest. The same legislation is applied without any adjustment to uneven-sized forests (Hyvän metsänhoidon suosittukset, 2001).

In spite of the current legislation which is not favourable for uneven-sized management, many forest owners are interested in it and ask for more freedom in treating their forests. Uneven-sized management has gradually gained popularity also among the general public (Lähde *et al.*, 1999). Similar development has taken place already in the 1980s in both North America (Franklin, 1989) and Central Europe (Kenk, 1995). These changes in people's opinions and encouraging financial returns obtained from uneven-sized forests are forcing forestry authorities to see uneven-sized forest management as a realistic option. Therefore, there is a need to develop management instructions for uneven-sized forest management in Finland.

Management instructions should show optimal management based on analytical and repeatable calculations (Cancino and Gadow, 2002). Optimization of uneven-sized forestry in Finland has become possible because growth and yield models, specifically targeted to uneven-sized forests, have recently been developed (Pukkala *et al.*, 2009). These models are based on a large dataset, and cover all types of site throughout Finland. The model set consists of individual-tree diameter increment, height and survival models and a model for ingrowth. The model set describes the dynamics of trees larger than 5 cm in diameter at breast height (d.b.h.). The ingrowth models predict the number of trees that will pass the 5 cm limit during the next 5-year period.

In the optimization of uneven-sized forestry, it is possible to seek optimal steady-state stand structures and cutting schedules (e.g. Adams and Ek, 1974; Chang, 1981; Bare and Opalach, 1987; Muchiri *et al.*, 2002; Trasobares and Pukkala, 2004). The results of these optimizations typically show the optimal post-cutting diameter distribution with a given management objective (Adams and Ek, 1974; Chang, 1981; Bare and Opalach, 1987) but there are also other possibilities to specify the optimized variables (Hotvedt and Abernethy, 1989; Trasobares and Pukkala, 2004). Optimal sustainable post-thinning diameter distribution is the simplest and most general management instruction for uneven-sized forestry (Lähde *et al.*, 1999). Another possibility is to optimize a sequence of cuttings so as to transform a certain stand into optimal uneven-sized structure (e.g. Haight, 1985; Haight *et al.*, 1985; Haight and Getz, 1987). In these optimizations, the optimal steady-state structure may be taken as a constraint, which must be reached during a certain time period, or the final structure may be optimized simultaneously with the transformation cuttings. These optimizations yield better management advice for individual stands, but since the results are stand specific, the results do not serve as overall management instructions.

The simplest way to optimize uneven-sized management is to optimize the post-thinning diameter distribution with a fixed cutting cycle. In the calculations, the post-thinning stand is left to grow for a cutting cycle, using simulation software, after which the frequencies of trees in different di-

ameter classes are reduced to their initial levels. This results in a certain harvest. The incomes and harvesting costs are calculated from the sizes and frequencies of harvested trees. Problems may arise when the frequency of a certain diameter class (after simulating growth for one cutting cycle) is less than the initial post-thinning frequency, for instance due to insufficient ingrowth. These situations need to be prevented when formulating the optimization problem.

There are several ways to describe the post-thinning diameter distribution of a stand. The simplest way is to use the frequencies of diameter classes directly as decision variables to be optimized (Adams and Ek, 1974). This approach results in a stepwise distribution, and the number of decision variables is high if the diameter classes are narrow. Another approach is to optimize the parameters of a theoretical distribution function such as beta, Weibull or Johnson's SB (Bare and Opalach, 1987; Gove and Fairweather, 1992; Trasobares and Pukkala, 2004). With this option, the number of optimized variables is much smaller, but there is less flexibility in the shape of the diameter distribution.

Direct search methods such as the cyclic coordinate, Rosenbrock and Hooke–Jeeves methods can be used to find optimal values for continuous decision variables in cases where the function to be maximized or minimized is a simulator that consists of individual-tree models (Bazaraa *et al.*, 1993). Linear programming can be used in some cases when the growth and yield model is a transition matrix (Buongiorno and Michie, 1980; Michie, 1985). A commonly used optimization method in stand level analyses is the Hooke–Jeeves method (Hooke and Jeeves, 1961; Roise, 1986; Haight and Monserud, 1990a; Valsta, 1992a, b; Pukkala and Miina, 1998, 2005; Miina and Pukkala, 2000; Möykkönen *et al.*, 2000). However, a recent study by Pukkala (2009) has shown that a new type of methods, which belong to the category of evolutionary computing, work better than the Hooke–Jeeves method in the optimization of even-aged management. In Pukkala (2009), the best evolutionary computing method was a differential evolution. However, since alternative methods perform differently in different problems, it is not known whether differential evolution would be the best method also in the optimization of uneven-sized management.

The aim of this study was to find the optimal steady-state structure of uneven-sized pine and spruce stands in Finland when maximizing the profitability of forestry (net present value (NPV)). Before doing these optimizations, alternative ways to formulate and solve the optimization problem were compared, and the best method was chosen. The effects of management objective and cutting interval on the optimal stand management were also analysed. Finally, the profitability of uneven-sized management was compared with the profitability of even-aged management.

## Methods

### *Problem formulations*

This study optimized the post-thinning diameter distribution on an uneven-sized forest. When calculating the

objective function value for a certain distribution, a stand of this distribution was first generated. Then, its development was simulated for one cutting cycle using the individual-tree models of Pukkala *et al.* (2009). After simulation, the frequencies of trees in different diameter classes were reduced to their initial levels. Removals, net incomes and NPVs were calculated from the dimensions and frequencies of removed trees.

Four different ways to describe the diameter distribution were analysed (Figure 1):

- 1 Frequencies of 4-cm wide diameter classes
- 2 Smoothed frequencies of 4-cm wide diameter classes
- 3 Weibull distribution
- 4 Johnson's SB distribution

In all cases, the distribution was sampled at 0.5-cm intervals, starting with 5.25 cm. The result was a set of sample trees that represented the stand in simulation. The reason for using 5 cm as the lower limit is that the ingrowth and other models of Pukkala *et al.* (2009) have been developed with this diameter as the minimum.

When frequencies of 4-cm diameter classes were used as decision variables (option 1), the frequencies of all sample trees falling within a given diameter class were equal (Figure 1). In the case of smoothed frequencies, a cubic spline function was fitted to the decision variables, and the frequencies of sample trees were obtained from

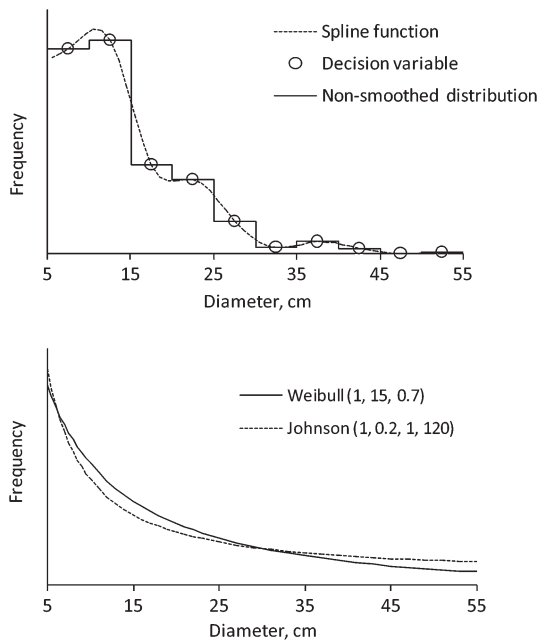


Figure 1. The four different ways to describe the diameter distribution of an uneven-sized stand. In the first two methods (non-smoothed distribution and spline function), the decision variables were the frequencies of diameter classes. In the other methods, decision variables were total number of trees and the parameters of distribution functions (Weibull or Johnson's SB).

the spline function (Figure 1). In this case, the frequencies of sample trees within a 4-cm diameter class were unequal.

When using the Weibull or Johnson's SB function, the optimized decision variables were the parameters of the function, together with the total number of trees per hectare. The Weibull function is (e.g. Gadow, 1984; Bare and Opalach, 1987; Gove and Fairweather, 1992)

$$f(d) = \left(\frac{c}{b}\right) \left(\frac{d-a}{b}\right)^{c-1} \exp\left[-\left(\frac{d-a}{b}\right)^c\right],$$

where  $d$  is diameter,  $f(d)$  is frequency of diameter  $d$ ,  $a$  is minimum diameter,  $b$  is a location parameter and  $c$  is a shape parameter. The Johnson's SB function is (e.g. Johnson, 1949; Hafley and Schreuder, 1977)

$$f(d) = \frac{\delta}{\sqrt{2\pi}} \frac{\lambda}{(d-\xi)(\xi+\lambda-d)} \exp(0.5z^2),$$

with

$$z = \lambda + \delta \ln\left(\frac{d-\xi}{\lambda+\xi-d}\right),$$

where  $\xi$  is the minimum and  $\lambda$  the range of the distribution, and  $\gamma$  and  $\delta$  are shape parameters.

In all four methods to describe the post-thinning distribution, the maximum diameter retained in thinning was used as an additional decision variable; post-thinning frequencies of all trees larger than this diameter were taken as zero. Therefore, in the case of Weibull function, the optimized variables were the total number of trees, parameters  $a$ ,  $b$  and  $c$  of the distribution function and the maximum diameter (five decision variables). There was one more decision variable when Johnson's SB was used because this function has two shape parameters. When frequencies were used, the number of diameter classes was 10 (with class mid-points of 7, 11, 15, . . . , 43 cm), which means that the number of optimized decision variables was 11.

#### Optimization methods

The tested optimization methods were differential evolution (Storn and Price, 1997), particle swarm optimization (Kennedy and Eberhart, 1995), evolution strategy (Bayer and Schwefel, 2002) and the method of Nelder and Mead (1965). All these methods operate with several solution vectors (sets of decision variables), which are combined to form a new solution vector. If the new solution is good, it replaces one of the earlier solutions. When repeating the process of generating new trial solutions and replacing old ones for many iterations, the average quality of the solutions gradually improves. The solution of the optimization problem is the best solution vector at the end of the last iteration.

Although all these methods are evolutionary algorithms, each of them has some specific features. For example, evolution strategy and the Nelder–Mead method concentrate on replacing the worst solution by a better one at every iteration

whereas particle swarm optimization updates all solutions at every iteration. Differential evolution compares, during each iteration, every solution to a new trial solution which is only slightly different and replaces the solution if the trial is better. The Nelder–Mead method differs from the others so that, after producing the initial solution vectors, there is no stochasticity in its search process.

All the above optimization methods were used exactly in the same way as explained in Pukkala (2009). The elements of the initial solution vectors were randomly drawn from a uniform distribution:

$$x_j = U[a_j, b_j], j = 1, \dots, m,$$

where  $x_j$  is the value of decision variable  $j$ ,  $a_j$  and  $b_j$  are, respectively, the lower and upper limit of variable  $j$ ,  $m$  is the number of decision variables and  $U$  stands for uniform distribution. The search was stopped when a pre-defined maximum number of iterations were completed. The search was stopped earlier if the difference in the objective function value between the best and the worst solution vector was less than 1 per cent of the best objective function value.

### Objective function

The objective variable which was maximized was the NPV of all future incomes and costs (also called land expectation value). The NPV was calculated from (Chang, 1981; Hall, 1983; Bare and Opalach, 1987; Trasobares and Pukkala, 2004):

$$NPV_T = \frac{N_T}{(1+i)^T - 1} - C_T,$$

where  $N_T$  is the net income obtained regularly at  $T$ -year intervals ( $\text{€ ha}^{-1}$ ),  $T$  is the length of the cutting cycle (years) and  $C_T$  is the value of the initial investment ( $\text{€ ha}^{-1}$ ). The value of the initial investment was calculated as the difference in roadside value between two options: (1) the landowner sells all trees and (2) the landowner sells only a part of the trees and leaves some trees to continue growing:

$$C = (R_{\text{All}} - H_{\text{All}}) - (R_{\text{part}} - H_{\text{part}}),$$

where  $R_{\text{All}}$  and  $H_{\text{All}}$  are, respectively, roadside value and harvesting cost in the case that all trees are sold, and  $R_{\text{part}}$  and  $H_{\text{part}}$  are, respectively, roadside value and harvesting cost in the case that only a part of trees are sold, i.e. the post-thinning number of trees of the uneven-sized management schedule are left to continue growing.  $C$  is the difference in net income between the clearfelling and selection felling options. It is the actual investment that the forest owner must make if she wants to use uneven-sized management.

The roadside values of timber assortments correspond to the mean timber prices in Finland in 2008. They were spruce and pine sawlog  $60 \text{ € m}^{-3}$ , spruce pulpwood  $38 \text{ € m}^{-3}$  and pine pulpwood  $33 \text{ € m}^{-3}$ . The harvesting costs were calculated with the model of Valsta (1992a) for a

thinning treatment. When the profitability of uneven-sized forestry was compared with even-aged forestry, stumpage prices were used instead of roadside prices because the results for even-aged forestry were available with stumpage prices. The used stumpage prices were spruce and pine sawlog  $58 \text{ € m}^{-3}$ , spruce pulpwood  $23 \text{ € m}^{-3}$  and pine pulpwood  $17 \text{ € m}^{-3}$ .

The objective function, which was maximized in optimizations, was obtained as the difference between the objective variable and a penalty function:

$$\text{OF} = \text{NPV} - \text{Penalty}.$$

The penalty function was required to guarantee sustainability, i.e. that the frequency of each diameter class at the end of a cutting cycle was at least the same as the initial frequency. The penalty was calculated from

$$\text{Penalty} = \sum_{i=1}^n (|f_i^t - f_i| \times i \times 200),$$

where  $f_i^t$  is the frequency of trees in diameter class  $i$  at the end of cutting cycle, i.e. after simulating stand development for  $T$  years and simulating a thinning treatment at the end of the cycle,  $f_i$  is the initial frequency of trees in diameter class  $i$  and  $n$  is the number of diameter classes. Multiplier  $i$  in the formula means that lack of large trees was penalized more than lack of small trees.

### Optimizations

Optimizations were done for two forest site types (Cajander, 1949) of pine and spruce. With spruce, the forest site types were *Oxalis-Myrtillus* (OMT) and *Myrtillus* (MT), and with pine they were MT and *Vaccinium* (VT). OMT is a fertile herb-rich heath whereas MT represents a mesic heath of medium fertility and VT a sub-xeric heath of rather low fertility. These forest site types are the ones in which most spruce and pine forests can be found. Within each site type, optimizations were done for three different temperature sums, 1300, 1100 and 900 degree days (d.d.). A temperature sum of 1300 d.d. is common in South Finland, 1100 in Central Finland and 900 d.d. in North Finland.

## Results

### Problem formulation and optimization method

Two optimization problems were solved 10 times with each optimization method and each way to describe the post-thinning diameter distribution. In the first problem, the NPV with 2 per cent discounting rate and 20-year cutting cycle was maximized in a spruce stand growing in southern Finland on a fertile site (OMT). In the second problem, sawlog production of the same stand was maximized with 20-year cutting cycle.

Of the four methods to describe post-thinning diameter distribution, the use of frequencies of 4-cm diameter classes was the worst method in most cases (Figure 2). The use of spline smoothing improved the result slightly. Optimizing the parameters of theoretical distribution functions together with the total number of trees and maximum retained diameter always worked well, except when the Nelder–Mead algorithm was used to optimize the parameters of Johnson’s SB function. The Weibull function gave better results than Johnson’s SB. The only exception was maximization of NPV with differential evolution where Johnson’s SB was better.

The Nelder–Mead method was clearly inferior to the other three optimization methods, which were very close to each other when the parameters of distribution functions were optimized. When NPV was maximized, the best method was particle swarm optimization with the spline function and the second best was evolution strategy optimization with the Weibull function. When maximizing sawlog production, evolution strategy with Weibull function was the best combination, with a clear difference to particle swarm optimization and spline function. The second best were particle swarm optimi-

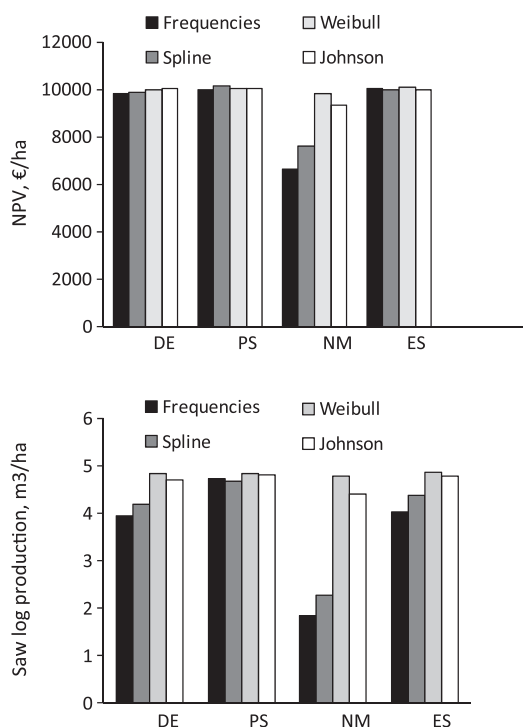


Figure 2. Mean NPV with 2% discounting rate (top) and annual sawlog production (bottom) in 10 repeated optimizations with four optimization methods and four ways to describe the post-thinning diameter distribution in a spruce stand on OMT site (herb-rich heath) in South Finland (DE = differential evolution; PS = particle swarm optimization, NM = Nelder–Mead method; ES = evolution strategy optimization).

zation and differential evolution, both with the Weibull function.

The methods were also compared in the following optimizations. First, the problem was solved 10 times, starting with different initial populations of solution vectors. The best solution vector found in these 10 optimizations was retained. Then, another five optimizations were conducted, taking the best solution vector found so far as one member of each new population. The other vectors were produced in the normal way. These additional optimizations may also be understood as a single optimization, in which the diversity of the solution vectors is returned at regular intervals. The additional optimizations often improved the solution, and they never reduced the quality of the solution.

In these optimizations, particle swarm optimization with the spline function found the best solution when NPV was maximized, closely followed by evolution strategy with Weibull function. With the sawlog production goal, evolution strategy optimization with the Weibull function was the best combination, followed by differential evolution with Weibull function.

On the basis of the above comparisons, evolution strategy optimization with the Weibull distribution was judged to be the best method, and it was used in all the remaining optimizations in the study. Every problem was solved so that 10 independent optimizations were done first, and the best solution vector was retained and used as one member of the initial population in five additional optimizations.

### Optimal management

The optimizations produced the optimal total post-thinning number of trees larger than 5 cm in d.b.h., parameters of the Weibull distribution and the maximum diameter retained in thinning (Figure 3). These results were converted into ordinary stand characteristics, which were calculated for both pre- and post-thinning stands, because this way of showing the optimal management is much easier for practitioners to understand compared with reporting the optimal Weibull parameters (Table 1, Figure 4)

When NPV with 2 per cent discounting rate was maximized with 20-year cutting cycle, a common feature of the results was that all trees larger than 18–20 cm in d.b.h. were removed (Figure 3). This means that all or almost all sawlog-sized material should be harvested if economic profitability is maximized (Table 1). The optimal post-thinning diameter distribution was of the reverse J shape, with the exception that the frequencies of trees larger than 18–20 cm were zero. The pre-thinning distributions also resembled reverse J but sometimes there were signs of bimodality in the distribution, the second peak being in small sawlog-sized trees of 19–25 cm in d.b.h. (Figure 4). The optimal harvesting removed almost exclusively sawlog-sized trees (Figure 4). However, from the pre- and post-thinning stand volume and sawlog volume of Table 1, it can be seen that often ~50 per cent of the removal was pulpwood. This is because a great part of the volume of small-sized log trees is pulpwood and some trees were also harvested from smaller diameter classes.

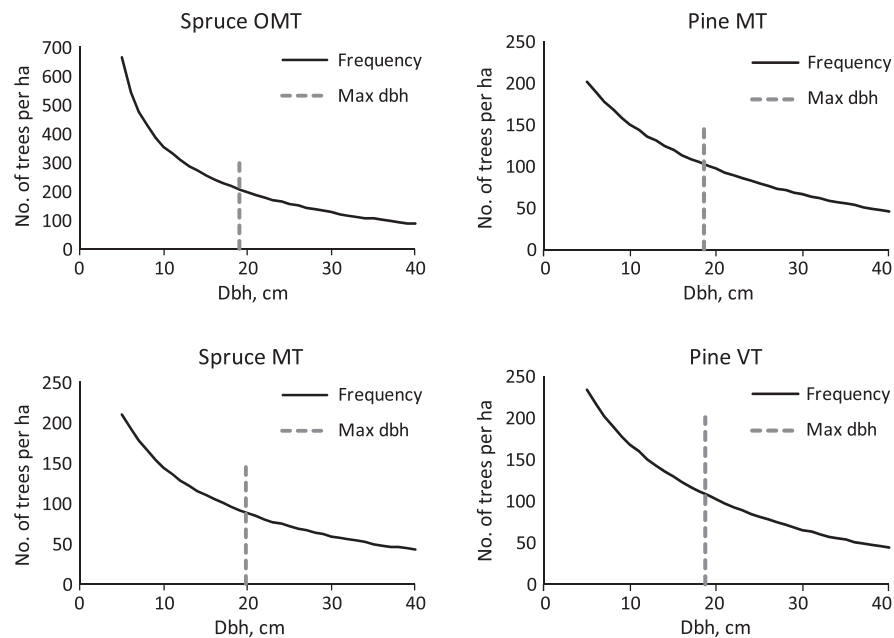


Figure 3. Optimal post-thinning diameter distributions in spruce and pine stands on two forest site types with temperature sum of 1100 d.d. (Central Finland) when NPV with 2% discounting rate is maximized. All trees with d.b.h. larger than 'Max d.b.h.' are removed in the thinning. OMT is fertile herb-rich heath, MT is medium fertile mesic heath and VT is sub-xeric heath with rather low fertility.

The pre- and post-thinning basal areas were clearly higher for fertile herb-rich (OMT) spruce stands than for pine stands or mesic spruce stands of medium fertility (MT) (Table 1). In OMT spruce stand, ~50 per cent of basal area was removed whereas the removal was typically two-thirds of stand basal area in pine and MT spruce. When the thinning intensity was expressed in terms of number of trees, it was often one-fourth to one-third of trees. The largest removed trees were 29–33 cm in spruce stands in South Finland and 25–29 cm in North Finland. In pine, the largest trees in the pre-thinning stand were 25–29 cm. The total thinning removal with a 20-year cutting cycle varied from 69 m<sup>3</sup> ha<sup>-1</sup> of sub-xeric (VT) pine in North Finland to 145 m<sup>3</sup> ha<sup>-1</sup> of OMT spruce in South Finland.

#### Effect of management objective

The effect of management objective on the optimal post-thinning diameter distribution was quite clear: the maximum retained diameter and the post-thinning basal area decreased with increasing discounting rate, and larger trees were retained when sawlog production was maximized (Figure 5, Table 2). The shape of the distribution was also different in pine and spruce with much more uniform distribution in pine. When profitability was maximized, using NPV as the objective variable, the maximum retained diameter was smaller than when maximizing net income or sawlog production (Figure 5). This is because NPV takes into account the opportunity cost of remaining trees, which

is much higher for sawlog-sized trees than for smaller trees. The remaining sawlog volume was always zero or close to zero when NPV was maximized whereas some log-sized trees of 21–25 cm in d.b.h. (sometimes up to 29 cm) were retained when sawlog production or net income was maximized (Table 2).

The pre- and post-thinning basal areas were the highest when sawlog production was maximized (Table 2). From the diameter distribution of Figure 5, it can be seen that the mean tree size and the maximum retained d.b.h. were clearly larger with this management objective than with the other objectives. This resulted in higher opportunity cost and lower profitability. For example, in OMT spruce stand, the NPV, calculated with 2 per cent discounting rate, was 6542 € ha<sup>-1</sup> when maximizing sawlog production, 7905 € ha<sup>-1</sup> when maximizing net income, 8392 € ha<sup>-1</sup> when maximizing NPV with 1 per cent discounting rate and 7655 € ha<sup>-1</sup> when maximizing NPV with 4 per cent discounting rate. Therefore, maximization of sawlog production resulted in the lowest economic profitability.

In both species, increasing discounting rate decreased the value of the post-thinning stand, which was an expected result (Figure 5). This reduction was achieved by reducing both the basal area and maximum diameter of the post-thinning stand. In a spruce stand, also the pre-thinning basal area decreased with increasing discounting rate whereas in a pine stand, it remained almost constant.

Maximization of different objective variables was used to find the maximum production and net income in uneven-sized forestry (Table 3). The maximum annual wood

Table 1: Optimal management of uneven-sized spruce and pine stands when NPV is maximized with 2% discounting rate and 20-year cutting cycle

	Spruce OMT*		Spruce MT†		Pine MT†		Pine VT‡	
	Before	After	Before	After	Before	After	Before	After
South Finland (1300 d.d.)								
No. of trees per hectare	1553	1151	564	358	691	422	705	448
Basal area, m <sup>2</sup> ha <sup>-1</sup>	27.7	11.2	14.4	3.9	15.9	4.6	15.4	5.0
Volume, m <sup>3</sup> ha <sup>-1</sup>	215	70	120	25	124	29	114	31
Sawlog volume, m <sup>3</sup> ha <sup>-1</sup>	86	0	63	0	50	0	42	0
No. of trees by d.b.h. class (cm)								
7	508	497	136	135	147	143	148	146
11	347	336	109	106	145	132	164	149
15	268	244	83	83	121	119	113	113
19	179	75	71	34	99	28	92	40
23	121	–	61	–	93	–	77	–
27	105	–	62	–	86	–	–	–
31	24	–	43	–	–	–	–	–
Central Finland (1100 d.d.)								
No. of trees per hectare	1662	1243	723	510	761	506	797	564
Basal area, m <sup>2</sup> ha <sup>-1</sup>	26.9	12.3	15.8	5.8	15.1	5.4	15.2	6.2
Volume, m <sup>3</sup> ha <sup>-1</sup>	205	77	127	38	114	34	110	38
Sawlog volume, m <sup>3</sup> ha <sup>-1</sup>	72	0	59	2	37	0	32	0
No. of trees by d.b.h. class (cm)								
7	639	553	192	188	190	188	211	211
11	339	333	146	144	169	151	164	164
15	254	252	121	116	126	125	156	132
19	174	106	86	62	126	42	112	57
23	150	–	89	–	94	–	111	–
27	106	–	65	–	56	–	42	–
31	–	–	24	–	–	–	–	–
North Finland (900 d.d.)								
No. of trees per hectare	1517	1068	1099	862	825	623	933	709
Basal area, m <sup>2</sup> ha <sup>-1</sup>	23.4	10.6	18.8	9.0	15.2	7.2	15.1	7.4
Volume, m <sup>3</sup> ha <sup>-1</sup>	176	67	143	57	113	47	104	45
Sawlog volume, m <sup>3</sup> ha <sup>-1</sup>	54	0	49	0	27	1	21	0
No. of trees by d.b.h. class (cm)								
7	601	447	351	351	215	215	275	274
11	300	300	240	238	181	178	227	218
15	230	226	184	180	159	149	166	166
19	185	95	148	93	137	80	158	51
23	130	–	123	–	102	–	107	–
27	70	–	54	–	21	–	–	–

‘Before’ is before cutting and ‘after’ is stand status after cutting.

\* Fertile herb-rich heath.

† Medium fertile mesic heath.

‡ Sub-xeric heath with rather low fertility.

production of uneven-sized forest varied from 3.2 m<sup>3</sup> ha<sup>-1</sup> of VT pine stand in North Finland to 7.8 m<sup>3</sup> ha<sup>-1</sup> of OMT spruce stand in South Finland. There was quite a clear production difference between OMT spruce and MT spruce stands. The maximal sustainable sawlog production of uneven-sized forestry was as high as 4.9 m<sup>3</sup> ha<sup>-1</sup> a<sup>-1</sup> in OMT spruce stand in South Finland. The lowest value, 1.5 m<sup>3</sup> ha<sup>-1</sup> a<sup>-1</sup>, was obtained for VT pine stand in North Finland.

#### Effect of cutting cycle

The effect of cutting interval on the optimal pre- and post-thinning stand basal area was expected: with increasing

cutting interval, the pre-thinning basal area increased and post-thinning basal area decreased (Figure 6). The shapes of the optimal post-thinning diameter distributions were very similar with different cutting cycles (results not shown), but the maximum retained diameter tended to decrease slowly with increasing length of cutting cycle (Figure 6).

Cutting cycles of 10, 15 and 20 years produced almost the same NPV with 2 per cent discounting rate. However, 10 and 15 years seem to be slightly more profitable, at least in fertile spruce stands, than the 20-year interval used in this study. Cutting intervals longer than 20 years are already too long for maximal profitability on a fertile site with 2 per cent discounting rate.

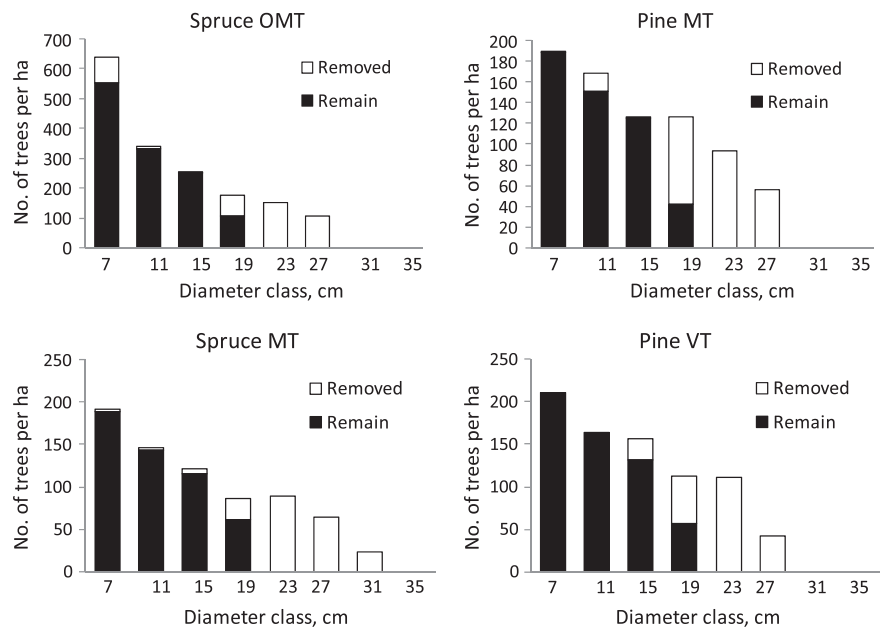


Figure 4. Optimal pre-thinning (removed + remain) and post-thinning (remain) frequencies of 4-cm diameter classes in spruce and pine stands in two forest site types with temperature sum of 1100 d.d. (Central Finland) when NPV with 2% discounting rate is maximized with 20-year cutting cycle. OMT is fertile herb-rich heath, MT is medium fertile mesic heath and VT is sub-xeric heath with rather low fertility.

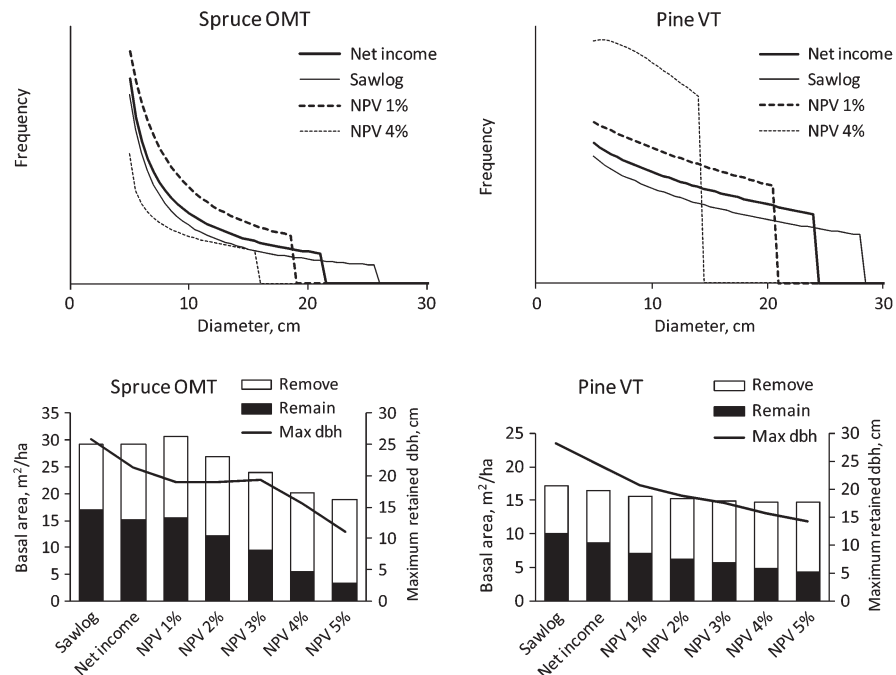


Figure 5. Effect of management objective on the optimal post-thinning diameter distribution (top), and optimal pre- and post-thinning stand basal area and maximum retained diameter (bottom) in Central Finland (1100 d.d.). OMT is fertile herb-rich heath and VT is sub-xeric heath with rather low fertility.

#### Comparison to even-aged forestry

Pukkala (2005) developed models that predict the NPV of even-aged forestry in the optimal management as a function of tree species, timber price, discounting rate, temperature

sum and forest site type. These models are based on thousands of optimizations of even-aged management. Planting and other stand establishment costs were also included in the optimizations but they had fixed values since their



Table 2: Optimal uneven-sized management in OMT spruce and VT pine stands in Central Finland with 20-year cutting cycle when maximizing net income, sawlog production or NPV with 1 or 4% discounting rate

	Net income		Sawlog		NPV 1%		NPV 4%	
	Before	After	Before	After	Before	After	Before	After
Spruce OMT* (1100 d.d.)								
No. of trees per hectare	1679	1377	1490	1281	2069	1685	1303	737
Basal area, m <sup>2</sup> ha <sup>-1</sup>	29.1	15.1	29.2	17.0	30.7	15.5	20.2	5.4
Volume, m <sup>3</sup> ha <sup>-1</sup>	227	100	236	122	228	96	150	30
Sawlog volume, m <sup>3</sup> ha <sup>-1</sup>	90	13	112	29	71	0	49	0
No. of trees by d.b.h. class (cm)								
7	634	603	601	573	812	796	447	391
11	332	332	271	270	448	448	360	230
15	240	237	183	178	324	313	185	115
19	188	185	137	132	213	127	145	–
23	131	20	109	105	178	–	99	–
27	113	–	90	23	94	–	67	–
31	41	–	76	–	–	–	–	–
35	–	–	23	–	–	–	–	–
Pine VT† (1100 d.d.)								
No. of trees per hectare	649	517	589	490	732	546	797	564
Basal area, m <sup>2</sup> ha <sup>-1</sup>	16.4	8.7	17.1	10.1	15.6	7.1	15.2	6.2
Volume, m <sup>3</sup> ha <sup>-1</sup>	127	61	136	75	116	46	110	38
Sawlog volume, m <sup>3</sup> ha <sup>-1</sup>	53	14	66	25	39	4	32	0
No. of trees by d.b.h. class (cm)								
7	143	143	126	124	172	172	211	211
11	119	119	101	101	149	148	164	164
15	105	101	87	72	133	128	156	132
19	92	87	75	62	102	98	112	57
23	81	67	66	47	107	–	111	–
27	72	–	65	–	69	–	42	–
31	37	–	50	–	–	–	–	–
35	–	–	20	–	–	–	–	–

'Before' is before cutting and 'after' is stand status after cutting.

\* Fertile herb-rich heath.

† Sub-xeric heath with rather low fertility.

variation is small compared with timber price fluctuations. The models give the NPV of bare land, i.e. the starting point is a clearfelled stand. The predictions of these models were compared with the NPV of the optimal management schedules of uneven-sized stands using the same stumpage prices of timber assortments for both even-aged and uneven-sized forestry. The assortment dimensions (minimum top diameter and piece length) were also the same.

The comparisons showed that even-aged and uneven-sized forestry give almost exactly the same NPV in OMT spruce in South Finland with all discounting rates (Table 4, Figure 7). In MT spruce, the two management systems were nearly equal with 1 per cent discounting rate. When discounting rate increased, uneven-sized management became more profitable. In Central and North Finland, uneven-sized forestry produced higher NPVs also on fertile sites (OMT). In MT, the relative superiority on uneven-sized management increased towards north (Figure 7).

In pine, even-aged and uneven-sized forestry were near each other only with 1 per cent discounting rate; with all higher rates, uneven-sized management was clearly superior (Table 4). Its superiority increased with increasing

discounting rate (Figure 7). Opposite to spruce stand, the effect of discounting rate on the performance of even-aged *vs* uneven-sized forestry was rather similar in South, Central and North Finland.

## Discussion

This study solved, for the first time in Finland, the optimal steady-state structure and management of uneven-sized forestry. All the structures and harvesting schedules are sustainable since it was required that the number of trees in each 4-cm diameter class at the end of a 20-year cutting cycle (before next cutting) is at least the same as the initial post-thinning frequency. This means that, in each diameter class, the ingrowth was at least the same as the loss of trees due to mortality and transition to the next diameter class.

Of the models used in the optimizations, those for diameter increment are based on a very large dataset (Pukkala *et al.* 2009). The model which predicts ingrowth to the smallest diameter class (5–9 cm) is based on a much smaller dataset and may be less reliable than the other models. The

Table 3: Maximum sustainable production ( $\text{m}^3 \text{ha}^{-1} \text{a}^{-1}$ ) and mean annual net income ( $\text{€ ha}^{-1} \text{a}^{-1}$ ) of uneven-sized forest with 20-year cutting cycle in South, Central and North Finland

	Spruce		Pine	
	OMT*	MT†	MT†	VT‡
South Finland (1300 d.d.)				
Wood production	7.8	5.6	5.3	4.7
Sawlog production	4.9	3.8	2.8	2.5
Net income	278	205	161	141
Central Finland (1100 d.d.)				
Wood production	6.9	5.3	4.5	3.9
Sawlog production	4.2	3.4	2.3	2.0
Net income	238	188	130	114
North Finland (900 d.d.)				
Wood production	5.8	4.8	3.6	3.2
Sawlog production	3.2	2.8	1.7	1.5
Net income	195	163	100	88

\* Fertile herb-rich heath.

† Medium fertile mesic heath.

‡ Sub-xeric heath with rather low fertility.

ingrowth model predicts clearly higher ingrowths in OMT spruce stands than in MT spruce or pine stands where high ingrowths are only possible with low stand basal area. Most probably, low ingrowth rate at higher stand densities is the main reason why the optimal post-thinning basal areas were low in pine and MT spruce stands. The total basal area of the post-thinning stand, including trees less than 5 cm in d.b.h., would be  $\sim 1 \text{ m}^2 \text{ha}^{-1}$  higher than the optimization results suggest.

The optimization results show that uneven-sized forestry enables reasonable timber production and income and is often more profitable than even-aged management if the stumpage price is the same in both cases. In reality, clear-felled timber of even-aged forestry can usually be sold with 10–20 per cent higher price, which improves the profitability of even-aged forestry. On the other hand, timber from the first commercial thinning of an even-aged stand often has a very low stumpage price. With high discounting rates, the high timber prices of final felling, which is done in the distant future, is compensated for by the low price of the first commercial thinning. However, if it is assumed that the timber price is 10 per cent higher in even-aged forestry, uneven-sized management still remains clearly more profitable with discounting rates of 2 per cent or more, except in OMT spruce stand in South Finland, where even-aged forestry is slightly more profitable.

The profitability comparisons concern situations in which even-aged management is optimal. With high discounting rates, this would mean low stand basal areas and very heavy high thinnings after the first commercial thinning and rather short rotations (e.g. Pukkala, 2006). If the profitability of uneven-sized forestry is compared with the current even-aged management practice, instead of the optimal, the advantage of uneven-sized management would be even greater than reported in this study.

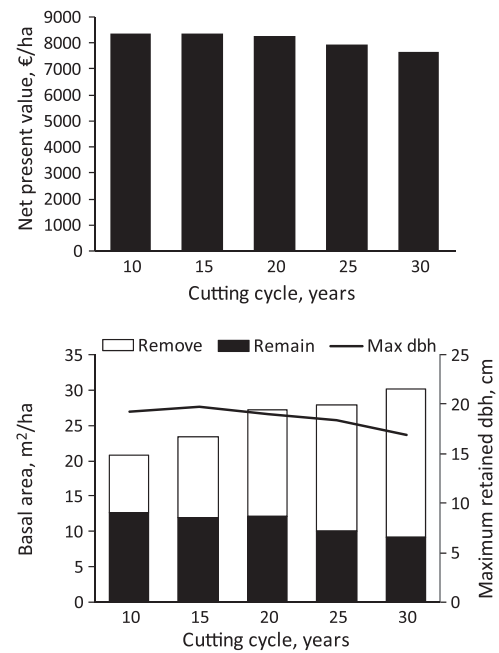


Figure 6. Effect of the length of cutting cycle on the NPV (with 2% discounting rate), optimal pre- and post-thinning basal area and the maximum retained diameter in an OMT (herb-rich heath) spruce stand in Central Finland (1100 d.d.).

Our results about the factors affecting the profitability of even-aged and uneven-sized forestry agree with previous research. For example, similarly to us, Chang (1981, 1990) found that uneven-sized management is more profitable than even-aged with high discounting rates. He also reported that the superiority of uneven-sized management increases when timber prices and the fixed harvesting cost are low (Chang, 1990). Chang (1981) and Hotvedt and Abernethy (1989) found that increasing discounting rate decreases the optimal stand basal area, which agrees with our results. In Hyytiäinen and Haight (2009), uneven-aged management was superior to even-aged forestry with higher discounting rates in mixed conifer forests in northern Idaho with or without fire risk. Increasing fire risk increased the relative efficiency of even-aged management. Tahvonen (2008), using a rather simple transition matrix model, found that uneven-aged forestry is more profitable than even-aged in a spruce stand in eastern Finland. According to Tahvonen (2008), optimal management may shift from even aged to uneven aged when discounting rate or planting cost increases or timber price decreases. Sánchez Orois *et al.* (2004) found that, in Galician maritime pine forests, uneven-sized management is more profitable on poor sites whereas even-aged management is better on fertile sites. This is in agreement with our finding that decreasing site quality increases the superiority of uneven-sized management.

Similarly to our observations, Schulte *et al.* (1999) concluded that maximization of sawlog production results in low profitability but maximization of economic profitability results in reasonably high sawlog production. Haight and

Table 4: NPV (€ ha<sup>-1</sup>) of even-aged and uneven-sized forestry in spruce and pine stands with different discounting rates in South, Central and North Finland

Discounting rate (%)	Spruce OMT*		Spruce MT†		Pine MT†		Pine VT‡	
	Even	Uneven	Even	Uneven	Even	Uneven	Even	Uneven
South Finland (1100 d.d.)								
1	26480	27222	20673	19954	12767	16062	11028	13924
2	11506	11576	7800	8504	5023	7010	3956	5957
3	6358	6538	3695	4937	2447	4063	1721	3415
4	4050	4177	1998	3203	1335	2624	816	2173
5	2896	2858	1216	2185	798	1774	411	1450
Central Finland (1100 d.d.)								
1	20087	22609	15057	18082	10897	12555	9295	10943
2	7442	9543	4532	7432	3878	5354	2948	4595
3	3450	5307	1583	4217	1670	3025	1982	2559
4	1818	3333	562	2659	781	1889	398	1553
5	1077	1667	192	1359	386	687	136	552
North Finland (1100 d.d.)								
1	14575	17870	10360	15283	9176	8969	7711	7883
2	4260	7356	2146	6180	2881	3653	2088	3212
3	1424	4045	353	3371	1041	1925	590	1706
4	468	2510	7	2062	374	1129	129	950
5	140	1673	0	1357	122	554	0	445

In uneven-sized forestry, the cutting cycle is 20 years.

\* Fertile herb-rich heath.

† Medium fertile mesic heath.

‡ Sub-xeric heath with rather low fertility.

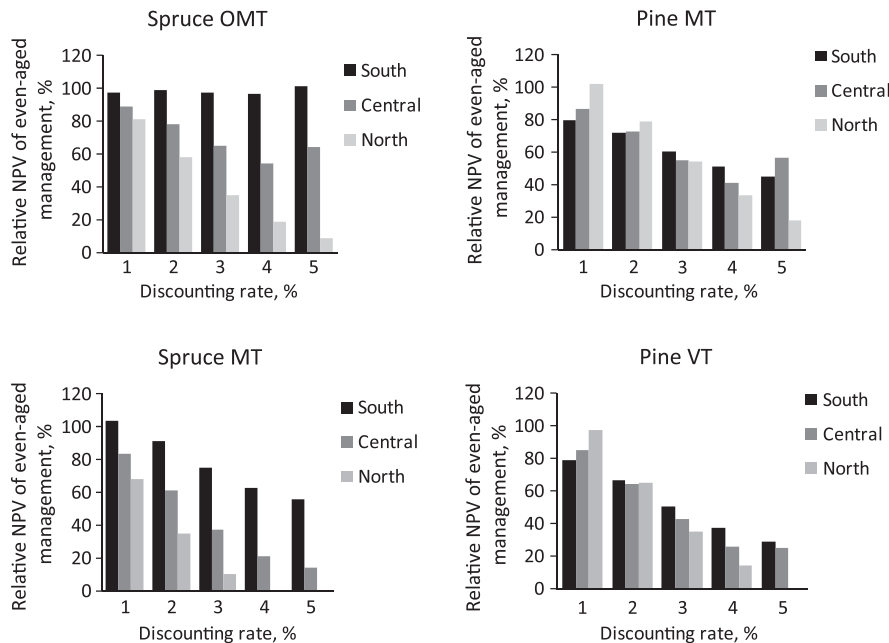


Figure 7. Relative NPV of even-aged forestry (% of the NPV of uneven-sized forestry) in optimal management in South (1300 d.d.), Central (1100 d.d.) and North Finland (900 d.d.) in the most common growing sites of spruce (OMT and MT) and pine (MT and VT). OMT is fertile herb-rich heath, MT is medium fertile mesic heath and VT is sub-xeric heath with rather low fertility.

Monserud (1990b) studied any-aged management alternatives, which allow combinations of even-aged and uneven-sized practices. They found that in the mixed conifer forests of Northern Rocky Mountains uneven-sized management

was more profitable than even-aged management. When yield was maximized instead of profitability, uneven-aged shelterwood system was found to be equally productive as even-aged plantation management.

The optimal post-thinning diameter distribution of an uneven-sized stand was usually a reverse J curve with a cut-off diameter within 18–21 cm. The shape of the optimal distribution was similar as in Haight *et al.* (1985). When sawlog production was maximized, the cut-off diameter was higher, often ~25 cm, and when NPV was maximized with high discounting rate (4 or 5 per cent), the cut-off diameter was less than 18 cm. The optimal diameter distributions resemble the ones which were found the most productive in the simulations of Pukkala *et al.* (2009), namely ‘rotated sigmoid curves’ in which the post-thinning frequency of trees decreases close to zero between diameters 19 and 23 cm. The obvious reason for this result is that the growth rate, and especially the relative value increment, begins to decrease sharply when the tree reaches this size (Chang, 1981). The value increment is the greatest in trees which are close to sawlog size because the value of these trees will soon increase instantly when the stems become large enough to give one sawlog.

This study optimized the steady-state structure of uneven-sized forests. The results can be applied directly to a stand which can be converted into the optimal post-thinning structure in one thinning. This stand must have enough trees in all diameter classes and plenty of regeneration smaller than 5 cm in d.b.h. This is possible only in stands which are already uneven sized. Therefore, our study does not answer the question of how a particular stand, which is not uneven sized, should be managed. To find answers to this question there are two options. The first one is to optimize a certain number of transformation cuttings with the constraint that after the last transformation cut the stand structure should have the optimal steady-state structure. The other alternative is to optimize the transformation cuttings and steady-state management simultaneously (Haight, 1985; Haight *et al.*, 1985).

Another question which needs attention in the research of uneven-sized management is to find the optimal degree of spatial heterogeneity (Haight and Getz, 1987). In Finland, where solar angles are low and the species are not particularly shade tolerant, regeneration and ingrowth are enhanced by creating small gaps to the canopy (e.g. Eerikäinen *et al.*, 2007). This means that there should be spatial variation in stand density. On the other hand, an aggregated spatial distribution of trees reduces growth compared with the regular distribution. Therefore, there exists an optimal degree of spatial variation, which can be found by using distance-dependent models in calculations, especially for regeneration and ingrowth. Fortunately, such models already exist in Finland (Eerikäinen *et al.*, 2007).

The optimal management of uneven-sized forest may also be temporally heterogeneous, so that a sequence of heavy selection fellings is conducted to enhance regeneration and ingrowth (Haight and Monserud, 1990b). Once plenty of new regeneration is established, another selection felling removes most large trees, after which a period of light felling follows. This method may also enable the foresters to get birch and pine regeneration in spruce stands, which makes it possible to utilize the different growth rhythms of tree species to increase production and profitability. For example, Haight *et al.* (1985) found that allowing temporal fluctuations in manage-

ment improved the profitability of uneven-sized management by 5 per cent. This result means that, strictly speaking, our study did not necessarily reveal the optimal management and potential profitability of uneven-sized management of Finnish forests; further improvements may be found by optimizing a sequence of diameter distributions instead of a single static equilibrium distribution. Another possibility is to allow any-aged management (Haight and Monserud, 1990b) in which planting of new trees every now and then is also an option.

#### *Conflict of Interest Statement*

None declared.

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