Effect of Species Composition on Economic Return in a Mixed Stand of Norway Spruce and Scots Pine

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Vettenranta, J. 1996. Effect of species composition on economic return in a mixed stand of Norway spruce and Scots pine. Silva Fennica 30(1): 47–60.

The effect of species mixture was studied in a mixed stand of Norway spruce and Scots pine by simulating around 100 different treatment schedules during the rotation in a naturally regenerated even-aged stand located on a site of medium fertility in North Karelia, Finland. Both thinning from below and thinning from above were applied. Optimum rotations were determined by maximising the net present value calculated to infinity and different treatment schedules were compared with the net present value over one rotation as per rotation applied. In the optimum treatment programme, the proportion of pines was decreased by half of the basal area in the first thinning stage and by the end of the rotation to about one third. In thinning from above, the proportion of pines can be maintained at a slightly higher level. It is economically profitable to maintain the growing stock capital at approximately the level recommended by Forest Centre Tapio, a semi-governmental forestry authority. With non-optimum species composition, the loss in net present value over one rotation can be about 10 % in thinning from below and about 20 % in thinning from above.

Keywords Scots pine, Norway spruce, mixed forests, net present value, soil expectation value, treatment programmes, growth models.
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Accepted April 1, 1996

List of Symbols

i_d = future 5-year diameter growth of tree (mm)
t = breast height age of tree (a)
d = diameter at breast height of tree (cm)
h = height of tree (m)
D5 = basal area weighted mean diameter of trees within a circle (r = 5 m) centred on the subject tree (cm)
CI(p) = competition index computed from pine competitors (rad)
CI(s) = competition index computed from spruce competitors (rad)
G = stand basal area (m^2/ha)
p = random plot factor
e = random tree factor
s_k = distance of neighbour k (m)
d_k = diameter (cm) of neighbour k (cm)
d_i = diameter of the subject tree (cm)
T_g = stand age at breast height (a)
H_g = basal area weighted mean height (m)
H_d = dominant height of the stand (m)
D_g = basal area weighted mean diameter (cm)
N = number of stems (stems/ha)
V = stand volume (m^3/ha)
R_T^H = income from cutting (FIM)
C_T^H = expenditure (FIM)
NPV = net present value (FIM)
T = time (stand age) (a)
u = regeneration age of present stand (a)
H = treatment alternative
L = soil expectation value (FIM)
i = interest rate (%)
StR = stumpage revenue (FIM)
NS = Norway spruce
SP = Scots pine
A = thinning from above
B = thinning from below

1 Introduction

Only a few investigations have been made of mixed stands in Finland (Lappi-Seppälä 1930, Mielikäinen 1980, 1985). Valsta (1986) studied harvesting programmes for mixed stands of pine and birch. The growth of pine and spruce in mixed stands has been studied only by Pukkala et al. (1994) with non-extensive study material as their basis. However, about 20 % of the forested area of southern Finland is composed of mixed stands of pine and spruce (Kuusela and Salminen 1983). In the study by Pukkala et al. (1994), it was found that mixed stands of pine and spruce on sites of medium fertility grow better than pure stands of pine or spruces, i.e., spruce and pine grow better together than separately.

Abroad several studies have been made about mixed stands. Mixed forests of Norway spruce and Scots pine has been studied by Jonsson (1962) in Sweden and Kerr et al. (1992) in Great Britain. Productivity of mixtures of other tree species has been studied by e.g. Tham (1988) and Kerr et al. (1992).

In addition to greater productivity mixed stands may also possess other advantages, e.g. more treatment alternatives and preservation of biodiversity. There are several problems associated with growing pure conifer stands on sites of medium fertility. There is the quality problem of saw timber in pine stands while in spruce stands the problem is that of soil deterioration (Mikola 1954).

The results of studies on pure stands cannot be applied in mixed stands because pine and spruce have different growth rhythms during rotation and the competition between individuals of the same species may be more intense than between different species. There are neither growth models nor treatment regimes for conifer mixtures in Finnish conditions.

During the past two decades, a few studies have been made in Finland about thinning from above; e.g. Vuokila (1970, 1977), Hynynen and Kukkola (1989), Mielikäinen and Valkonen (1991). In coniferous forests, thinning from above has been found to be comparable with thinning from below, often economically even more profitable (especially in pine stands). Other advantages of thinning from above include improved stem quality, preventing stems from becoming oversized, longer rotations if so required and more versatility in treatment alternatives.

When considering the economic aspects, two facts must be borne in mind. First, the value growth of the growing stock (stand yield) and second, the opportunity cost of invested growing stock capital. In the commercial thinnings harvesting becomes profitable when the decrease in

future value growth caused by decreasing the growing stock capital is smaller than the interest received from the harvesting income. This harvesting principle presupposes continued tree-by-tree harvesting. When the harvesting costs are included in the calculations, the frequency of thinnings will decrease while their intensity will increase. Regeneration becomes profitable if the mean value growth of future forest generations (compare with soil expectation value in formula 7) is higher than the present value growth.

The higher the woodland owner's opportunity cost, the higher and earlier the incomes from harvesting are preferred. These are brought about in two ways: by increasing either the amount of removal or its unit value (Vuokila 1970). An increase in removal decreases the value growth of remaining growing stock. Conversely, the unit value of removal can be increased by removing the biggest trees in the stand (contrary to the conventional practice of thinning from below).

The public is showing increasing interest in forest management. There is criticism of single-objective treatment programmes and impairing of woodland biodiversity. The forestry profession must comply with the demands of society if these are economically and ecologically reasonable. Simple automatic decisions can no longer be made. We need information about stand growth, the meaning of tree species composition and the consequences of different treatment alternatives.

The aims of this study are to determine (1) the optimum tree species ratio in Norway spruce Scots pine mixture during the rotation, (2) the optimum thinning schedule, and (3) the loss of income in non-optimum cases. Aims 1 and 2 cannot be treated separately because they affect each other.

2 Material and Methods

The growth of one real plot was simulated applying different treatment alternatives. The said stand is naturally regenerated and nearly even-aged, located in North Karelia, Finland (63°40'N, 31°5'E, 80–100 m a.s.l.). Slightly more than half of the growing stock (slightly less than 200 trees) of the stand is composed of Scots pine with the rest being Norway spruce (Table 1). Trees are partly in groups by species (Fig. 1). The study plot is 0.09 ha in area, quite a typical study plot area in Finland (Gustavsen 1980). The stand is established on site of medium fertility (MT, Myrtillus site type (Cajander 1909)).

The diameter distribution of the stand is such that normal first cutting by number of stems according the Forest Centre Tapio (Metsänhoitosuositukset 1989) cannot be simulated at all, because of the numerous small stems (Fig. 2). If cutting were to be simulated by number of stems, the basal area would be reduced so much that it would cause a marked loss in stand growth.

Table 1. Stand variables in the study material, where SP = Scots pine, NP = Norway spruce, T_g = stand age at breast height, H_g = basal area weighted mean height, H_d = dominant height of the stand and D_g = basal area weighted mean diameter.

Species	G m^2/ha	N stems /ha	V m^3/ha	T_g a	H_g m	H_d m	D_g cm
SP	11.1	1000	72	17.5	12.1	13.2	15.6
NP	6.8	900	37	18.3	10.6		11.9

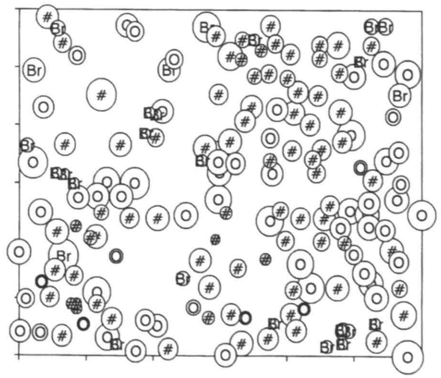


Fig. 1. Crown map of the stand used in growth simulations. Norway spruce (#), Scots pine (O), and broadleaved trees (Br).

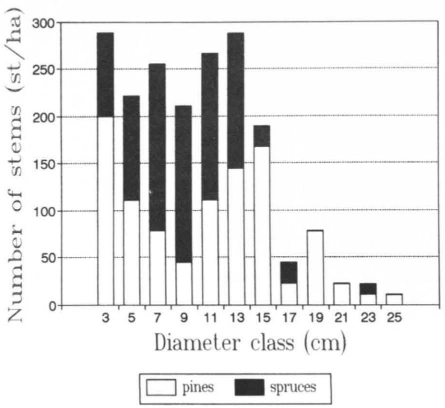


Fig. 2. Diameter distribution in the stand.

Stand growth was simulated using a simulator designed specially for Norway spruce-Scots pine mixtures on site of medium fertility (Pukkala et al. 1994). The stand growth was calculated as the sum of individual tree growth in five years period. The following spatial diameter growth models were applied in the simulator:

Scots pine (equation 4 in Pukkala et al. 1994)

$$\ln(i_d)_{ij} = 3.237 - 0.593\ln(t_{ij}) + 0.519\ln(d/D5)_{ij} - 0.0701CI(p)_{ij} - 0.0488CI(s)_{ij} - 0.221\ln(G_j) + p_j + e_{ij} \quad (1)$$

Norway spruce (equation 5 in Pukkala et al. 1994)

$$\ln(i_d)_{ij} = 3.327 - 0.791\ln(t_{ij}) - 9.062/(d_{ij}+5) + 0.333h^{0.5}{}_{ij} - 0.0081CI(p)_{ij} - 0.0668CI(s)_{ij} - 0.0489G_j + p_j + e_{ij} \quad (2)$$

where i_d = future 5-year diameter growth (mm), t = breast height age (a), d = diameter (cm), h = height (m), D5 = basal area weighted mean diameter of trees within a circle (r = 5 m) centred on the subject tree (cm), CI(p) = competition index computed from pine competitors (rad), CI(s) = competition index computed from spruce competitors (rad), G = stand basal area (m^2/ha), p is random plot factor and e is random tree factor. Subscript i refers to a tree and j to a stand or a plot.

Competition index (CI) is the sum of vertical angles (α) between a horizontal plane at a height of 0.8 times the height of the subject tree and the tops of the competitors:

$$CI = \sum_{k=1}^{n} \alpha_k \quad (3)$$

in which n is the number of competitors closer than 5 meters. Competition index for trees growing nearer than 5 meters to border was calculated with the assistance of trees growing in the 5-m border zone around study plot. Broadleaved trees that occurred in the plots used to provide the initial conditions were treated as pines.

Tree height increment was simulated using a spatial height model in which diameter, tree age and competition between trees were used as predictors (Pukkala et al. 1994). The tree height corresponding to its initial diameter at each simulation interval and the height corresponding the diameter after diameter growth for the interval was added, were calculated. The difference between these two heights was added to the real tree height. The height models were:

Scots pine

$$\ln(h-1.3) = 1.1440 - 12.980(d+5)^{-1} - 8.9345(t+5)^{-1} + 0.0142CI(p) + 0.6683\ln(G) \quad (4)$$

Norway spruce

$$\ln(h-1.3) = 4.0127 - 29.476(d+5)^{-1} - 0.4522d/t \quad (5)$$

Formula for competition index CI in height model:

$$CI = \sum_{k=1}^{n} s_k^{-1}(d_k / d_i) \quad (6)$$

where s_k = distance of neighbour k (m), d_k = diameter (cm) of neighbour k (cm) and d_i = diameter of the subject tree (cm).

Stand treatments during simulations were in accordance with the recommendations of the Forest Centre Tapio (Metsänhoitosuositukset 1989). However, in regard to the limits of the preparation material of the growth model, an attempt

was made to increase the pre-thinning basal area, because it was probable that mixed stands grow better at greater stand densities than pure stands (Pukkala et al. 1994).

All thinnings were made on a basal area basis. When thinning from below, a slight (removal 2–4 m^2/ha) random thinning was included to depict removal of big trees of poor quality. The minimum diameter of the removed trees was 9 cm, except in clear-fellings. The minimum distance between the remaining trees was 1.0 m in the first thinning and 1.2 m in the second. Smaller trees were removed from among trees located too close to each other. In this way both spatial pattern and the quality of a stand were improved during rotation as in practical forestry. Extraction routes within the stand were not simulated.

With dominant height about 16 m and basal area about 30 m^2/ha, stands were thinned from below applying different tree species ratios so that the post-thinning basal area was about 22 m^2/ha. The post-thinning proportion of pine was 45 % to 72 % of the basal area depending upon the simulated treatment (Appendix 1, 1–6; henceforth, the numbers in brackets refer to the number of the treatment alternative in Appendix 1). This was the widest possible range of post-thinning variation.

Second thinning was made 15 years later when basal area was about 35 m^2/ha and was decreased to 24 m^2/ha. The post-thinning proportion of pine varied from 15 % to 97 % of the stand's basal area.

When the optimum tree species ratio during rotation for a specified growing stock capital level was arrived at, an assessment was made as to whether the optimum changed if the growing stock capital were maintained at some other level by changing the intensity and timing of thinning (7–14).

The simulation period applied was 50 years, after which breast height age was about 70 years and the total stand age was about 85 years. This was believed to be sufficiently long for finding out the optimum rotation with thinning programs. Approximately 100 schedules were simulated.

Thinnings from below was followed by studying whether the different thinning method changed the optimum tree species ratio. The intensity of thinning was changed and the pre- and post-thinning stand basal areas were maintained at some other level as in the case of thinning from below. Thinning from above was simulated by removing trees starting from the largest until the required basal area limit for the species was achieved. In thinning from above the location of trees was not a constraint (19–33).

Rotation was determined by maximising the net present value calculated to infinity as the optimum rotation is different for every treatment programme. The investment problem in stand regeneration was formulated using Faustmann's (1849) theory of land interest as follows: there are M regeneration and treatment alternatives and alternative H maximising the net present value calculated to infinity should be found.

$$\text{Max NPV} = \frac{\sum_{T=0}^{u} R_T^H (1+i)^{u-T} - \sum_{T=0}^{u} C_T^H (1+i)^{u-T} + L}{(1+i)^u} \quad (7)$$

where R_T^H = income from cutting (FIM), C_T^H = expenditure (FIM), NPV = net present value (FIM), T = time (stand age) (a), u = regeneration age of present stand (a), H = treatment alternative, L = soil expectation value (FIM) and i = interest rate (%).

The invest problem of stand regeneration has been proved to be correctly formulated, when it is based on Faustmann's theory of land interest (e.g. Samuelson 1976). For example Salminen (1993) has used this formula to determine requirement for regeneration of understocked stands.

Cost of regeneration and tending of the stand were included in the soil expectation value. In this study, the soil expectation values (L) were determined by iterating with formula 8 and they were set as follows (compare with Salminen 1993):

Interest rate, (%)	Soil expectation value, (FIM/ha)
2	17000
3	6000
4	0

Felling costs were included in timber prices and they were expected to be as average stumpage prices in Southern Finland during cutting seasons 1991–1993 (Metsätilastollinen vuosikirja 1992):

Timber	Price (FIM/m^3)
Scots pine logs	200
Norway spruce logs	160
Scots pine pulpwood	70
Norway spruce pulpwood	90

Proportions of timber assortments were calculated according to taper curve and volume functions by Laasasenaho (1982), where minimum diameter of pulp wood was 6 cm and top diameter of pine logs was 14.1 cm and spruce logs 16.1 cm.

The net present value to infinity was calculated by prolonging harvesting income to the moment of regeneration applying the selected interest rate and then discounting the sum and the soil expectation value to the time of stand establishment.

$$\text{Max NPV} = \frac{\sum_{T=0}^{u} StR(1+i)^{u-T} + L}{(1+i)^{u}} \qquad (8)$$

where StR = stumpage revenue (FIM).

By examining the net present value from the moment of stand establishment to infinity using formula 8, the optimum rotation of each treatment programmes was determined by the point of maximum. Following this, the profitability of treatment alternatives were compared on the basis of the net present values over one rotation (formula 8 without the soil expectation value) of the rotation in question. Net present value over one rotation was used because the net present value calculated to infinity assumes selected equal yield of future tree generations as described by the constant soil expectation value depending on the interest rate. If the treatment alternatives were compared on the basis of the net present values calculated to infinity, it would assume that future tree generations would be treated in same way. The net present values over one rotation indicate the real difference between the yields of the treatment alternatives during one rotation.

4 Results

4.1 Thinning from Below

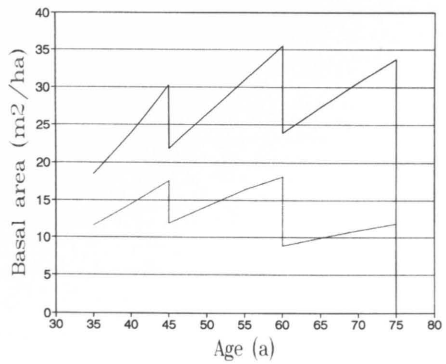
Maximum net present value over one rotation, and interest rates of 2 % and 3 % with thinning from below was where the proportion of pine was decreased at first thinning to 55 % and at second thinning to 37 % of the total basal area (5) (Fig. 3). In this case the pre-thinning basal areas were 30.3 m^2/ha and 35.5 m^2/ha. With an interest rate of 4 %, the best result was obtained with a slightly smaller proportion of pine and with only one thinning (4).

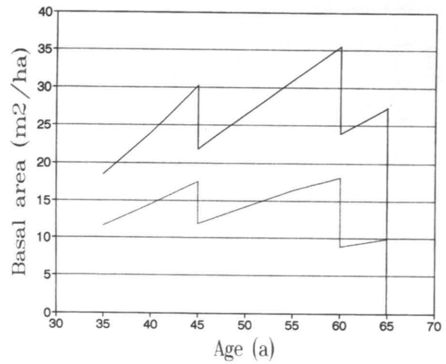
When applying three less intense thinnings, controlling proportions of tree species is easier, but the land value did not rise in comparison to the more intense thinnings. (10–14). At stand age 55 years, growth was vigorous despite high stand density. If the stand was thinned at this stage, its growth decreased dramatically (Table 2). The optimum rotation in this case was so short that there was no time for a third thinning. Only in the case where the proportion of pine was decreased to one fifth of the basal area, was the optimum rotation long enough to allow three thinnings (14).

When thinnings were less intense and average stand density was high, the optimum proportion of pine increased (especially when applying high interest rates, 11–12). With post-thinning basal area set at 24 m^2/ha, the optimum proportion of

Table 2. The change in the growth of pine and spruce when harvesting a 55-year-old stand applying thinning from below. The pre-thinning basal area was about 30.3 m^2/ha and the post-thinning basal area about 22.3 m^2/ha. The pre-thinning proportion of pine was 53 % and the post-thinning proportion of pine was 43 %.

	Pine		Spruce		Pine and spruce
	Relative %/5a	Absolute m^3/ha/5a	Relative %/5a	Absolute m^3/ha/5a	Absolute m^3/ha/5a
Pre-thinning	14.5	20	26.1	31	51
Post-thinning	14.8	12	22.9	25	37





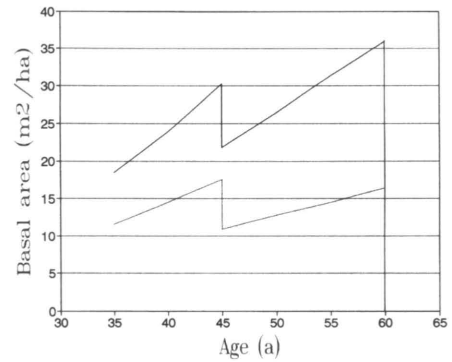


Fig. 3. The optimum treatment programme and the proportion of pine when applying interest rates of 2 % (top left), 3 % (top right) and 4 % (left). Total stand basal area (—), and basal area of pines (····).

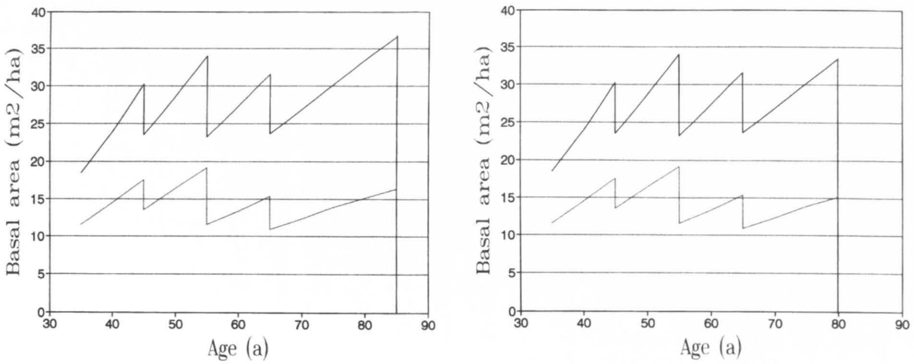
pine at the end of the rotation was about half of the basal area (12).

The optimum rotation in a stand treated with thinning from below is 65–75 years when applying an interest rate of 2 %, 55–70 years with an interest rate of 3 %, and 55–65 years with an interest rate of 4 %, depending on the treatment programme. When the interest rate is 4 %, the optimum rotation is so short that there is often time for one thinning only. When the proportion of spruce grows, the rotation becomes longer, but the treatment programme as a whole seems to affect more the length of the rotation. The interest rate applied is the major factor affecting the rotation (Davis 1966).

If either spruce or pine are removed selectively as much as possible during the rotation, the net present value decreases by about 10 % (1,6). A stand transformed into an almost pure stand of spruce gives a slightly better result than a stand consisting almost entirely of pine. Volume of a stand transformed to pure pine is about 10 % less, and its saw timber production is about 20 % less, than that of the best alternative. This comparison assumes a rotation of 85 years.

4.2 Thinning from Above

In the best alternative with low interest rates, the stand's pre-thinning basal area is raised 30, 34 and 32 m^2/ha and then reduced in three thinnings to 23–24 m^2/ha (31) (Fig. 4). The optimum proportion of pine is a little higher than in thinning from below. The proportion of pine is reduced over the rotation from 58 % to 46 %. Almost the



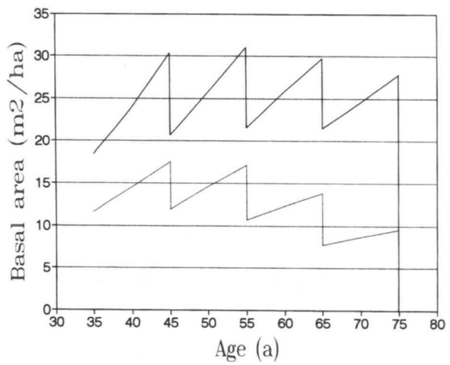


Fig. 4. The optimum treatment programme and the proportion of pine when applying three thinnings from above and interest rate of 2 % (top left), 3 % (top right) and 4 % (left). Total stand basal area (—), and basal area of pines (····).

same total yield is obtained if the proportion of pine is reduced by half (32). With the interest rate at 4 %, the optimum mean growing stock capital is a little smaller and the optimum proportion of pine at the end of the rotation is a little over one third (30).

With basal area reduced to 22 m²/ha at first thinning, to 20 m³/ha at the second, and the proportion of pine at 56 %, the best yield of the alternatives of two thinnings obtained; i.e. equal to about 98 % from the best alternative (22) (Fig. 5). The total volume yield over a rotation of 85 years is only about 2 % smaller than in the best alternative.

Optimum rotations are clearly longer when applying thinning from above than thinning from below. With interest rate at 2 %, the optimum rotation in almost all cases is 85 years, occasionally even longer. When interest rate is 2 % the optimum is quite a flat. With interest rate at 3 %, the optimum rotation is 75–80 years with a few exceptions. With the interest rate at 4 %, the optimum is 70–80 years. The rotation can be extended by conducting many light thinnings; net present value over one rotation does increase, although the net present value calculated to infinity will not improve.

When removing spruce in thinning from above during the rotation (19) and removing pine only when necessary to meet the basal area required at the thinning, the net present value is about 80 % compared to the best alternative (31). When removing pine during the rotation by applying thinning from above, with no spruce removed at all (20), the net present value is about 10 % smaller than in the best alternative (31). The total volume yield over a rotation of 85 years is about 10 % lower in pure stands of pine at the

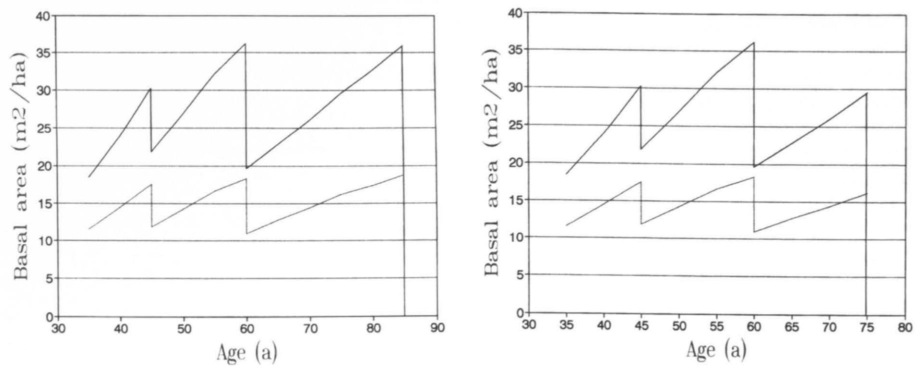


Fig. 5. The optimum treatment programme and the proportion of pine when applying two thinnings from above and interest rate of 2 % and 3 % (left) and 4 % (right). Total stand basal area (—), and basal area of pines (····).

end of the rotation than in stands of spruce. The yield of saw timber is only about 3 % lower.

4.3 Comparison of Thinning from Below and Thinning from Above

In almost all cases, regardless of the intensity of thinning and the tree species ratio, thinning from above gave greater net present value than the best alternative of thinning from below irrespective the fact that thinning from above was realized schematically.

The greatest net present values with different interest rates were

2 %	3 %	4 %
19500	10100	5500

By removing trees through thinning from above, the profitability of thinning is improved thanks to early, high harvesting income resulting from the high volume of the removed trees and the better relative growth of small trees as compared to big trees (Vuokila 1970). Due to these facts, the best net present value, produced by thinning from below, was only 86.0–88.5 % of the best alternative of thinning from above (Fig. 6).

When the first thinning is executed as thinning

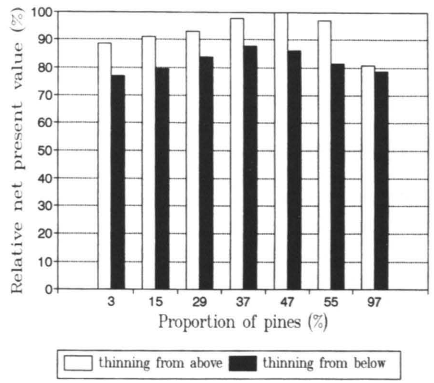


Fig. 6. Effect of tree species ratio on the relative net present value. Thinning from below is conducted at the ages of 45 and 60 years with corresponding pre-thinning basal areas at about 30 m²/ha and 35 m²/ha and post-thinning basal areas at about 22 m²/ha and 23 m²/ha. Thinning from above is conducted at the ages of 45, 55 and 65 years with pre-thinning basal areas at 30, 34 and 32 m²/ha and post-thinning basal areas at 23–24 m²/ha. Proportion of pines refers the relative stand basal area of pines after the last thinning.

from below in accordance with the recommendations of Forest Centre Tapio, so that the proportion of pine is decreased by half, and the second thinning is executed as thinning from above by further decreasing the proportion of pine, the net present value is slightly higher than the alternatives of pure thinning from below (15–18). With low interest rates, this method is more profitable, but with an interest rate of 4 %, the rotation will be so short that the profitability of thinning from above does not have time to manifest itself. The optimum proportion of pine is slightly over one third of the total stand basal area.

The significance of tree species ratio is slightly more pronounced when applying thinning from above. If spruce is removed in large quantity through thinning from above, the loss of income is significant (Fig. 6). This agrees with studies by Vuokila (1977), Mielikäinen and Valkonen (1991) and Eriksson (1990) in which thinning from above was found to be more suitable when dealing with pine than with spruce.

5 Discussion

The results obtained in this study suggest that on sites of medium fertility it is more profitable to grow pine and spruce in a mixture rather than as pure stands. Merely by adjusting the ratio of tree species the net present value can be influenced by 20 % over the rotation.

In the optimum treatment programme, the proportion of pine is lowered by first thinning from below at age of 45 years to approximately half of the basal area. In the second thinning, at the age of 60 years, the proportion of pine should be decreased from one third to half according to the treatment alternative. In thinning from above, the proportion of pine can be maintained at a higher level than in thinning from below. In the beginning, it is profitable to raise the stand's basal area in accordance with the recommendations of Forest Centre Tapio and then through thinning from below to reduce it to the recommended basal area stocking level. In thinning from above, the amount of the remaining growing stock should be maintained at a higher level.

The greatest net present value is obtained by applying three thinnings from above, but the difference when compared to applying two thinnings is so small that harvesting costs may compensate for it. Regardless of the thinning applied, it is economically profitable to raise the basal area to 35 m^2/ha at the age of 60 years; this is higher than the recommendations published by Forest Centre Tapio. On the other hand, it was not possible to determine the optimum density in this study because stand growth was simulated in periods of five years during which the basal area increases considerably. Another problem was encountered with the growth model. Optimum densities are presently in the upper part of the range of the data used in constructing the model. It is possible for the real optimum to be higher than that obtained in this study. It was not reasonable to raise the basal area over the limit of the data used in model construction because the growth models may not give reliable results when applying very high stand densities.

Extensive simulations were made only for one stand and little can be said about the effect of site fertility, variation in the spatial arrangement of trees, the diameter distribution of trees and the mixture of tree species in the early stages of stand development.

On certain sites, with both pine and spruce growing at almost equal rate, it is economically profitable to have a lot of pine in the early stages and then decrease their proportion over the rotation, so that at the end of the rotation the proportion of pine amounts to half or slightly less than that of the basal area. This result supports the idea that was proposed in the study of Pukkala et al. (1994). The treatment programme does not significantly affect the optimum species mixture.

The profitability of thinning from above is based partly on a high initial number of stems that remains high during rotation (over 1000 stems/ha at the end of the rotation). Stand growth is maintained at good level by releasing more small stems from the competition coming from big trees. The growth model does not take into account stand history; it computes growth based only on the present growing stock variables. It is probable that releasing trees from the suppressed status may cause overestimation of growth, because the growth vigour of such trees is not

comparable to that of dominant trees of the same dimensions. Stands in data used in the growth model were not thinned from above.

Another reason that makes results of thinning from above unreliable is the method of comparing different treatment programmes. With an interest rate of 2 %, the optimum of the net present value calculated to infinity is quite flat, especially when applying thinning from above. Minor changes in the treatment programmes and in the soil expectation value may result in removal of optimum rotation. This does not have much of an influence on the net present value calculated to infinity but the net present value over one rotation does clearly increase when the rotation is extended.

The theory of land interest has been criticized (e.g. Davis 1965, Oderwald and Duerr 1990). Its weakness in this study are: uncertainty of land expectation value, timing of costs and regeneration, and constant interest rates and timber prices over long rotations. Regardless of those aspects, the fact, that conifer mixture is economically more profitable than pure stands, can not be denied.

The manner of implementing thinning from above (selection of saw timber) was not probably optimal, as spatial pattern of trees was not taken into account. Because of this, and the aforementioned reasons, the results obtained for thinning from below and thinning from above are not quite comparable, but they do indicate that the optimum proportion of tree species does not significantly depend on the manner of thinning.

Another problem connected to the small sample plots is that the removal of individual trees may significantly influence the results. The study plot is so small that, especially when applying thinning from above, the proportion represented by an individual tree can be significant. However, the number of trees was numerous enough to allow flexibility in adjusting species composition, which was the main subject of this study.

In the simulations of thinning from above, tree location was not taken into account. It is probable that some big trees with good growth and little competition against other trees have been removed. Their role in total growth may be marked as a result of concurrent reduced evenness in the spatial arrangement. In this study two

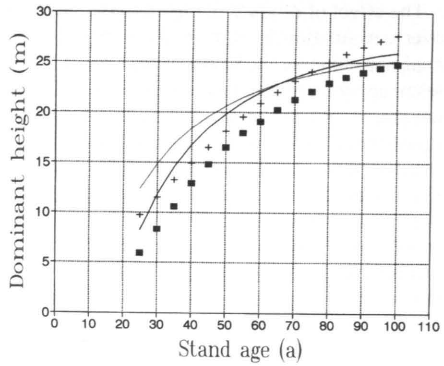


Fig. 7. Dominant height of pine (+ +) and spruce (■ ■) in pure stands (Koivisto 1959) and in mixed stands in accordance with the present study material. Pine (····), and spruce (—).

totally different management regimes show that the optimal species composition is not especially sensitive to this.

In the simulation model, the height growth of trees, especially of pine, decreases sharply in later stages of stand development. Height growth corresponds to real growth in the data used for constructing the height model (Fig. 7). Consequently, older stands in the data may be located on poorer sites than young ones. This is to be expected because better sites have a higher probability to being clear-felled at a younger stand age but may have resulted in underestimation of growth at the end of the rotation and would have affected calculation of the optimum tree species mixture.

Although older stands may be located on poorer sites than younger stands, it does not explain why the curves for dominant height intersect at the age of 65 years. This may be due to the effect of species mix. Pine may suffer from competition from spruce, or the lack of the competition from pine may slow height growth. On the other hand, pine may promote height growth of spruce. According to height models, competition does not affect height growth of spruce, but the internal competition among the pine and growth in the stand's basal area promote the height growth of pine.

The effect of mixture on the net present value over one rotation is at most about 10 % when applying thinning from below and about 20 % when applying thinning from above. The loss of net present value is significant when the stand is transformed into a pure stand. When applying thinning from above and transforming the stand into a stand of pine, the net present value over one rotation is about 10 % less than in a stand transformed into stand of spruce. A stand transformed into a stand of spruce yields 10 % less than the best alternative. When the stand is treated with thinning from below, the difference between the final stand of pine or spruce is a minor one. It is a few percent more profitable to grow spruce stand. It is possible for the optimum thinning programme to change considerably when the stand is transformed into a pure stand; consequently, the results are not entirely comparable.

The results of this study agree with the results of Pukkala et al. (1994) about the profitability of admixture in coniferous forest. In that study the volume growth of mixtures was 3–15 % greater than the growth of pure stands. The results of this study also give support to the results of Vuokila (1970, 1977), Hynynen and Kukkola (1989) and Mielikäinen and Valkonen (1991) in which the profitability of thinning from above was found to be equal or better than thinning from below. In pine stands the profitability is clearer than in spruce stands. According to Mielikäinen and Valkonen (1991) thinning from above in pine stand was 10 % more profitable than thinning from below when comparing net present values over rotation with interest rate at 4 %. The manner of implementing thinning from above in this study was not exactly the same that was found optimal in spruce stand in the study of Valsta (1992) in which part of small trees were removed besides the big trees.

When the stand is grown as a spruce stand from the beginning, the net present values are probably worse than shown in this study, because spruce grows slowly at first and the benefit of the better growth of pine in a young stand is not enjoyed. Conversely, when spruce is removed just before beginning to grow more rapidly than pines, the result is probably not as good as in a stand consisting of only pine from the very start.

On poorer sites, the optimum growing stock capital decreases and optimum proportion of pine increases. There should be a method for determining site fertility with different species mixtures so that treatment instructions for practical application might be obtained. Also the precision of growth predictions of young trees after thinning should be improved by considering the vitality of trees, for example, with assistance of crown model. Numerous treatment alternatives and an abundance of starting situations with mixed stands, including changes in the price ratio of timber assortments and variation in the soil expectation value, the optimum growing stock capital and tree species composition should be determined by means of mathematical optimization.

Acknowledgements

I thank Prof. Timo Pukkala for reading the manuscript, Mr. Olli Salminen for his advice, Mr. Erkki Pekkinen and Prof. David Ford for revising the English.

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Appendix 1. Treatment alternatives, their net present values with different interest rates, yield and optimal rotation. T denotes total stand age, G the stand basal area before thinning and G* after thinning. SP-% denotes the proportion of pines after thinning, A thinning from above and B thinning from below.

Treatment alternative	1st thinning					2nd thinning					3rd thinning					Relative net present value with interest rate of			Yield on rotation of 85 years		Optimal rotation with interest rate of		
	T a	G m²/ha	G* m²/ha	SP-%	A/B	T a	G m²/ha	G* m²/ha	SP-%	A/B	T a	G m²/ha	G* m²/ha	SP-%	A/B	2 %	3 %	4 %	Total	Sawlog	2 %	3 %	4 %
1	45	30.3	21	72	B	60	33.6	22.1	97	B						78.8	78.6	82.4	492	273	70	60	60
2	45	30.3	21.9	68	B	60	34.6	23.4	55	B						81.5	82.9	85	522	350	70	65	60
3	45	30.3	21.8	53	B	60	34.6	23.8	48	B						86.1	85.9	85.9	551	379	75	70	60
4	45	30.3	21.9	50	B	60	36	23.7	29	B						83.8	84.2	88.1	552	367	70	60	60
5	45	30.3	21.8	55	B	60	35.5	23.9	37	B						87.8	86	87.4	560	381	75	65	65
6	45	30.3	22	45	B	60	35.4	23.4	15	B						79.6	81.8	81.8	539	341	70	70	60
7	45	30.3	18.7	61	B	60	31	21.3	54	B						78.8	83.6	86.1	501	344	65	65	60
8	45	30.3	18.7	61	B	60	31	21.2	42	B						79.7	84.7	86.4	512	354	65	65	65
9	45	30.3	17.8	47	B	60	29.3	21.7	40	B						74.6	77.4	80	490	311	70	65	60
10	45	30.3	18.7	61	B	55	27.1	21.9	57	B	65	27.7	21.2	55	B	75.4	77.1	84.3	480	319	65	55	55
11	45	30.3	23.8	58	B	55	33.2	23.7	50	B	65	30.7	23.8	46	B	79.6	83.9	86.3	521	350	65	65	60
12	45	30.3	23.7	50	B	55	33.4	23.6	32	B	70	33.4	23.4	20	B	80.1	81.8	83.8	523	328	70	65	60
13	45	30.3	21.8	55	B	55	31	22.8	43	B	65	29.4	23.8	37	B	78.3	83.4	85.4	522	351	65	65	60
14	45	30.3	21.8	50	B	55	31.3	22.1	34	B	70	31.8	23.6	19	B	82.2	82.5	85.6	519	338	75	65	60
15	45	30.3	21.8	50	B	60	34.8	19.4	49	A						84.9	85.7	86.1	523	324	75	70	70
16	45	30.3	21.8	50	B	60	34.8	19.8	40	A						90.7	88.1	86.6	544	345	85	75	70
17	45	30.3	21.8	50	B	60	34.8	23.2	49	A						89	85.4	84.8	549	354	85	75	65
18	45	30.3	21.8	50	B	60	34.8	23.2	37	A						91.4	87.5	85.8	565	370	85	75	70
19	45	30.3	23.9	74	A	55	33.7	24.1	98	A	65	30.2	23.1	97	A	78.8	78.6	82.4	497	309	70	65	60
20	45	30.3	23.9	48	A	55	34.3	23.9	23	A	65	31.9	24.1	3	A	88.4	90.1	93.1	548	320	85	70	70
21	45	30.3	21.8	55	A	60	36.2	23.8	38	A						95.4	94.4	92.3	571	342	85	75	70
22	45	30.3	21.8	55	A	60	36.2	19.6	56	A						97.7	97.6	97.1	561	331	85	85	75
23	45	30.3	21.8	55	A	60	36.2	19.9	45	A						96.8	95.7	97	560	330	85	75	75
24	45	30.3	21.8	55	A	60	36.2	21.8	55	A						96.7	95.7	95.3	567	336	85	80	70
25	45	30.3	21.8	55	A	60	36.2	21.9	50	A						97.4	95.5	96.3	571	342	85	75	75
26	45	30.3	21.4	59	A	60	35.5	22.8	39	A						94.9	95.3	96.1	571	335	80	75	70
27	45	30.3	21.4	59	A	60	35.5	17.6	50	A						88.9	90.2	92.2	526	281	85	80	70
28	45	30.3	21.4	59	A	55	30.8	21.6	54	A	65	29.2	21.5	46	A	92	91.8	94.1	532	296	85	75	75
29	45	30.3	20.7	57	A	55	31	21.6	49	A	65	29.7	21.7	46	A	97.1	98	99.5	551	314	85	80	75
30	45	30.3	20.7	57	A	55	31	21.6	49	A	65	29.7	21.5	36	A	96.4	97.4	100	552	312	85	75	75
31	45	30.3	23.5	58	A	55	34	23.2	50	A	65	31.6	23.6	46	A	100	100	99.3	573	346	85	80	80
32	45	30.3	23.5	58	A	55	34	23.6	57	A	65	31.6	23.5	50	A	99.3	99.3	99.1	569	338	85	80	75
33	45	30.3	23.5	58	A	55	34	23.5	41	A	65	31.8	23.5	37	A	97.7	97.7	98.3	571	338	85	75	75
34	50	35.3	15.5	50	A											93.6	92.6	94.6	557	324	85	75	75
35	50	35.3	15.7	51	B											74.4	76.4	81.2	496	300	70	60	60