Introduction

Control of stand density by thinning has been the major tool in regulating tree growth and improving timber quality. While thinning from below may increase the merchantable volume of a stand, usually it does not increase the total volume increment per unit area (e.g. Assmann, 1954; Carbonnier, 1967; Hasenauer et al., 1997; Zeide, 2001). Several studies have shown that volume increment of many tree species does not decline with decreasing stand density within a wide range of stand density (e.g. Hamilton, 1981; Horne et al., 1986). This indicates that thinning from below redistributes the increment from smaller trees to larger ones, and a smaller number of trees is able to produce the same volume increment per unit area. In order to increase the merchantable volume, or to decrease the total volume increment, the intensity, timing and frequency of thinnings have to be defined.

In Finland, Norway spruce (Picea abies (L.) Karst.) is economically and ecologically one of the most important tree species. The first growth and yield tables for Norway spruce were published by Blomqvist in 1872 (see also Heikkilä, 1914), but they were not widely applied. Systematic growth and yield studies began in the 1910s.
and the first results for Norway spruce were published by Ilvessalo (1920). They described the structure and development of fully stocked, naturally regenerated pure Norway spruce stands. A decade later, Cajander (1933) studied the development of planted, unthinned Norway spruce stands.

After World War II, selective thinnings, i.e., removing only the largest trees, were prohibited and thinnings from below were promoted (Anon., 1948; Kalela, 1948). At the same time, a research project was initiated to study the effects of thinnings on the structure and development of naturally regenerated Norway spruce stands (Vuokila, 1956; Kallio, 1957). However, the intensity of the thinnings was low and the removed trees were heavily suppressed or dying. In the early 1960s, the thinning intensity in practical forestry increased mainly due to the mechanization of harvesting operations. Because the short- and long-term growth effects of heavy thinnings were not known, a new research project was established and growth and yield tables, as well as thinning guidelines, were prepared for planted Norway spruce stands (Vuokila and Väliaho, 1980). During the last decades, growth models have been developed for forest management planning (e.g. Hynynen et al., 2002).

All the Finnish studies cited above were based on temporary sample plots (apart from the recent growth models that were based on remeasured inventory growth plots) because there was an urgent demand for growth and yield tables, but no data available. However, permanent sample plots provide more reliable results on long-term growth and stand dynamics. In Finland, the first thinning experiments were established in the 1920s and 1930s (Ilvessalo and Väliaho, 1980). During the last decades, growth models have been developed for forest management planning (e.g. Hynynen et al., 2002).

The objective of this study was to relate thinning intensity with diameter, height and volume increment on the basis of permanent long-term experiments with thinnings from below in planted Norway spruce stands. This study is a sequel to the reports of Vuokila (1975, 1980, 1985), which were based on the five experiments also used in this study. In this study, we expanded the database and used all the thinning experiments of the HARKAS series, established by the Finnish Forest Research Institute in Norway spruce stands (21 experiments). Only two stands which were fertilized before the establishment of the experiments were excluded from the data set. Many experiments have already been studied for over 30 years (Table 1) and they approach maturity or are already mature. This gives us an opportunity to investigate total stem volume production and thinning removal, as well as stand structure, during the whole stand rotation.
Materials and methods

The experiments

The material was collected from 21 thinning experiments in southern Finland (Figure 1). The experiments were established by the Finnish Forest Research Institute in the 1960s and early 1970s, apart from three experiments which were established in the late 1970s and early 1980s (Table 1). The stands were even-aged, pure or almost pure Norway spruce (Picea abies (L.) Karst.) stands located on mineral soil, and were established by planting with seed of local origin. The sites were classified as the Oxalis–Myrtillus or Myrtillus forest site type (Cajander, 1909), which corresponds to highly fertile or fertile sites typical for Norway spruce. The site index ($H_{100}$, dominant height at age 100 years in metres) ranged from 29 m to 36 m. Site indices were calculated using the functions of Vuokila and Väliaho (1980). Due to changes in land use (e.g. the construction of houses and roads), some of the experiments had to be terminated earlier than planned (Table 1).

The principal aim of the experiments was to investigate the effects of thinning intensity on growth and yield of Norway spruce stands at different stages of stand development. The material consisted of two separate sets: (1) thinning experiments based on stem number (13 experiments); and (2) thinning experiments based on stand basal area (eight experiments). The experiments based on stem number were originally planned to include three different treatments with varying thinning intensity and a number of repeated thinnings from below, as well as an unthinned control plot. The final stem number per hectare was planned to be the same in all the treatments, and it was to be reached using two heavy, three moderate or five light thinnings from below, based on a fixed number of stems remaining after the thinnings. However, it was soon noticed that, in many cases, the treatments resulted in only small differences among the plots and the research plan was therefore modified. The intensity of the later thinnings was increased in order to maintain the differences in stand density between the plots. In the experiments based on basal area, a constant basal area ratio compared with the unthinned control plot was maintained on the thinned plots, i.e. the plots were thinned to basal areas of 90, 75 and 60 per cent compared with the control plot.

Square or rectangular plots surrounded by a 5-m-wide buffer zone were established in each

Figure 1. Location of the experiments. For explanation of the onset stages, see Materials and methods.
The average area of the plots was 1000–1600 m² (range 500–2500 m²). Most of the experiments had four, eight or 12 plots, i.e. the four treatments were replicated in a randomized block design in the experiments with eight or 12 plots (Table 1). In the experiments with five, six or 10 plots, one or two of the treatments were additionally replicated within the experiments or blocks. In experiments Vh002 and Vh098, having only three plots, the light thinning intensity was missing (see below).

Measurements and statistical analysis

Following establishment, the experiments were measured between two and seven times (Table 1). The measurement period was on average 27 years. At the time of the last measurement, stand age ranged from 39 to 85 years. Tree species, stem diameter at breast height ($d_{1.3}$), and possible damage (fallen, broken, decaying, needle loss, etc.), as well as its cause (wind, snow, competition, insect or fungus species) and severity (temporary, causing permanent defects, lethal), were recorded for each tree on the plot. In the selection of sample trees, the probability for a tree to be selected was proportional to its diameter, but the sample trees were randomly located on the sample plots. Height, height to crown base, and stem diameter at 6 m height ($d_{6.0}$) were measured on each sample tree (on average, 54 per plot). The crown base was defined as the lowest whorl with at least one living branch that was separated from the other living whorls above it by no more than one dead whorl.

Stand characteristics for individual plots were

<table>
<thead>
<tr>
<th>No.</th>
<th>No. of plots</th>
<th>$H_{100}$</th>
<th>Year of planting</th>
<th>Establishment of plots</th>
<th>Last measured</th>
<th>Treatment onset†</th>
<th>No. of measurements</th>
<th>$H_{dom}$‡</th>
<th>No. of stems ha$^{-1}$§</th>
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Table 1: Characteristics of the experiments at establishment

* $H_{100}$ site index, dominant height at age 100 years (m).
† 1, early; 2, medium; and 3, late onset of the treatment based on the $H_{dom}/H_{100}$ ratio, see Materials and methods.
‡ Dominant height based on 100 largest trees ha$^{-1}$.
§ Before the onset of the treatments.
compared (1)

measured stem diameters (calculated using volume functions based on the 1994). Stem volumes of the sample trees were calculated using the KPL software developed at the Finnish Forest Research Institute (Heinonen, 1994). The heights of the other trees were predicted using Näslund’s height curve (Näslund, 1937) that was fitted for each plot with the help of the tree heights measured on the sample trees. The volume of the other trees was calculated using smoothing functions fitted to the sample tree data. The minimum length applied for pulpwod boles was 3.0 m and the minimum top diameter was 8.0 cm over bark. The stem wood below this size was considered as wastewood. The minimum length applied for timber logs was 3.7 m, and the minimum top diameter over bark was 19.5 cm. The minimum top diameter progressively decreased with increasing log length, being 16.0 cm when the log length was over 4.3 m.

Annual increments were calculated as the difference between successive measurements divided by the number of years between the measurements. The periodic growth between the measurements was corrected to correspond to the average climatic conditions using annual radial growth indices. The indices for Norway spruce in southern Finland were based on the increment cores measured in connection with the National Forest Inventory. The indices published by Henttonen (1986, 1990) were used for the period 1961–1979, and the indices by Henttonen (unpublished data) for the period 1980–1999. As no indices were available for the years 2000 and 2001, they were assumed to be average years. The method for calculating the growth indices is described in Henttonen (1986, 1990).

Because the number and intensity of the thinnings varied among the plots and experiments, the plots could not be classified into different groups in accordance with the original research plan. Therefore, the plots were grouped on the basis of the average basal area on the plot during the whole measurement period (BA) compared with that on the control plots of each experiment. The basal areas of the different measurement periods were weighted by the period length, i.e.

\[
BA = \sum_{i=1}^{n-1} T_i \cdot (BA_{i} + BA_{i+1})/2 T_{tot}
\]

where \(BA\) is the basal area of the remaining living trees at the beginning of each measurement period, \(BA_t\) the total basal area at the end of each measurement period including dead trees and trees to be thinned, \(T\) the length of each measurement period (years), \(T_{tot}\) the length of the total measurement period (\(\Sigma T_i\)), and \(n\) the number of individual measurement periods. The plots were classified as follows: (U) unthinned (average basal area \(\geq 95\) per cent of that on the control plots) – note that some plots with light thinning intensity were classified as unthinned because their basal area exceeded \(95\) per cent; (L) light thinning (85–94 per cent); (M) moderate thinning (70–84 per cent); and (H) heavy thinning (\(\leq 70\) per cent). In class H, the minimum and average relative basal areas were 55 per cent and 63 per cent, respectively.

Based on the ratio between dominant height (based on 100 by diameter of largest trees ha\(^{-1}\)) at the time of establishment and the site index \(H_{dom}/H_{100}\), the experiments were further divided into three thinning onset stages as follows: early onset \((H_{dom}/H_{100} \leq 0.49)\), medium onset \((0.50 \leq H_{dom}/H_{100} \leq 0.60)\) and late onset \((H_{dom}/H_{100} \geq 0.61)\). The mean \(H_{dom}/H_{100}\) ratio was 0.42, 0.54 and 0.71 for the early, medium and late onset stages, respectively. At the early onset stage, only light pre-commercial thinnings were carried out before establishment of the experiments. The stands of medium onset stage had already passed the first commercial thinning phase, but the thinnings carried out had been light. Accordingly, only light thinnings were carried out in the stands of late onset stage before establishment.

Statistical significance of the differences among the treatments was analysed using covariance analysis including random experiment and block effects. The model used to test the treatment effects was:

\[
Y = \mu + \delta_0 + \beta X_{sbp} + u_s + u_b + u_{sbp}
\]

where \(Y_{sbp}\) is a dependent variable, \(\mu\) is the overall mean, \(\delta_0\) the effect of stand density class, \(\beta\) the regression coefficient, and \(u_s\), \(u_b\) and \(u_{sbp}\) the random effects for stand \(s\), block \(b\) and plot \(p\). The initial differences among the plots were removed by applying a continuous covariate \((X_{sbp})\) measured before the onset of the treatment, i.e. mean stem diameter, dominant height (100 by...
Figure 2. Mean annual diameter increment of all the trees (parts a–c) and the 400 by diameter largest trees ha$^{-1}$ (parts d–f) on plots of different thinning intensity (U, unthinned; L, light; M, moderate; H, heavy thinning) and treatment onset stage (early, parts a and d; medium, parts b and e; late onset, parts c and f). Treatments marked with the same letter are not significantly different ($P \geq 0.05$). Stem diameter before the onset of the treatment was used as the covariate in equation 2.
diameter of largest trees ha$^{-1}$) or stand volume. The values shown in the figures and tables are adjusted by setting covariate effects to their mean values.

The pairwise comparisons were performed by computing generalized least-square means of the treatment effects. Owing to the unbalanced design, adjusted $P$-values for the multiple comparison were computed from the simulated distribution of a multivariate random vector. In the figures and tables, the treatments marked with the same letter are not significantly different ($P \geq 0.05$). Restricted maximum likelihood (REML) estimation in the MIXED procedure of SAS (SAS Institute, 1999) was used in the analysis.

**Results**

The arithmetic mean annual diameter increment of all the trees on a plot increased with decreasing stand density (Figure 2a–c). The differences between the thinning intensities were statistically significant at all treatment onset stages. Because the differences of the mean increment may be caused by different numbers of stems, mean diameter increment was also calculated for the 400 (by diameter) largest trees ha$^{-1}$. The differences between the treatments in the diameter increment of the largest trees were, however, similar to those for all the trees (Figure 2d–f). On the other hand, thinning intensity had no clear effect on annual dominant height increment (Figure 3).

On plots with light and moderate thinning intensity, the annual volume increment per hectare was about the same as on the unthinned plots at all treatment onset stages (Figure 4). Compared with the unthinned plots, a heavy thinning intensity decreased the volume increment per hectare during the whole measurement period by 8 per cent at the early onset stage. At the medium onset stage, a heavy thinning intensity decreased the volume increment even more (11 per cent), but the differences between the treatments were not statistically significant. At the late onset stage, the volume increments among the individual plots were very variable and, therefore, the differences between the thinning intensities were not statistically significant.

In addition to the analysis according to fixed treatment onset stages, the whole material was

![Figure 3](https://example.com/figure3.png)

Figure 3. Mean annual dominant height increment on plots of different thinning intensity and treatment onset stage. Dominant height before the onset of the treatment was used as the covariate in equation 2. For explanation of the symbols, see Figure 2.
also combined, i.e. the volume increments between the successive measurements were analysed according to the dominant height in the middle of each measurement period (Figure 5). The unthinned plots and heavy thinning intensity differed from each other at all dominant height stages. The annual volume increment of the light and moderate thinning intensity lay between those of the unthinned and heavy thinning plots, excluding the lowest and highest dominant height stages. However, the mutual order of the light and moderate intensities was variable at different dominant heights and it was not possible to distinguish between them.

Volume increments and basal areas on the thinned plots during the whole measurement period were also examined in relation to the mean volume increment and basal area of the unthinned plots in each experiment (Figure 6). Because the experiments had several unthinned plots, and their basal areas were also related to the mean value, some relative basal areas exceeded 100 per cent. Figure 6 clearly shows that the variation of relative volume increment was high among individual plots, but that the mean relative volume increment decreased only slightly with decreasing mean relative basal area.

As expected, the current stem volume per hectare decreased with increasing thinning intensity at all treatment onset stages (Table 2). However, total yield, calculated by summing up the current volumes of living trees and the volumes of thinned and dead trees, did not differ significantly between the unthinned plot and the light and moderate thinning intensities (Table 2). The heavy thinning intensity decreased the total yield by 7 per cent, 4 per cent and 7 per cent compared with the unthinned plots at the early, medium and late onset stages, respectively, but the differences at the medium and late onset stages were not statistically significant. On the unthinned plots, some of the trees had also been removed in connection with the thinnings (Table 2), because some of the thinned plots were placed in the ‘unthinned’ group if their basal area did not differ from the control plots >5 per cent. In addition, light sanitary thinnings were carried out in some experiments, i.e. dying trees were removed at the request of the landowner.

The current log volume was highest with the unthinned or light thinning intensity and lowest

Figure 4. Mean annual volume increment on plots of different thinning intensity and treatment onset stage. Total volume before the onset of the treatment was used as the covariate in equation 2. For explanation of the symbols, see Figure 2.
Figure 5. Mean annual volume increment between the successive measurements plotted against mean dominant height during each measurement period on plots of different thinning intensity. For explanation of the symbols, see Figure 2.

Figure 6. Volume increment on plot $i$ during the whole measurement period in relation to the mean volume increment on the unthinned plots of the same experiment ($iv_i/v_u$) plotted against the relative average basal area during the whole measurement period (related to that of the unthinned plots, $BA_i/BA_u$, see equation 1). The thick continuous line is a non-linear curve fitted to the data $[iv_i/v_u = (BA_i/BA_u)^2/(0.08 + 0.91BA_i/BA_u)^2], R^2 = 0.16]$. 
on the heavy thinned plots, even though the differences at the medium onset stage were not statistically significant (Table 2). Accordingly, the current volume of pulpwood and wastewood decreased with increasing thinning intensity at all treatment onset stages. In contrast, total volume of merchantable-sized timber, i.e. the current volume of logs and pulpwood summed up with that removed in thinnings, was about the same in all thinning intensities.

On the unthinned plots, volume of dead trees was higher than that on the thinned plots, especially in the later phases of the experiments (Figure 7). On the thinned plots, the differences in dead wood volume were small among the thinning intensities (Figure 7 and Table 2). At the late onset stage, dead wood volume was, however, about the same on the unthinned and light thinned plots. The initiation of the treatment did not result in a dramatic change in mortality. Instead, the mortality rate increased slightly in the later phases of the measurement period. On the other hand, the volume of logsized dead trees was relatively similar in all thinning treatments, i.e. the higher dead wood volume on the unthinned plots was mainly caused by the mortality of small-sized trees (Table 2).

Discussion

Total volume production per unit area was highest on the unthinned or lightly thinned plots, irrespective of the treatment onset stage. However, light and moderate thinning had almost no effect on volume increment, or total volume produced during the long measurement period. Only heavy thinning resulted in a clear reduction in volume increment. Even though the basal area of the heaviest treatments was, on average, 55–70 per cent below that on the

| Table 2: Total yield and its structure on plots of different thinning intensity (U, unthinned; L, light; M, moderate; H, heavy thinning) and treatment onset stages |
|---------------------------------|--------|--------|--------|--------|--------|
| Total volume (m³ ha⁻¹)          | U      | L      | M      | H      |
| Log                             | 349 a  | 384 a  | 374 a  | 377 a  |
| Pulp                            | 206 b  | 178 b  | 172 b  | 140 c  |
| Wastewood                       | 29 a   | 27 a   | 29 a   | 28 b   |
| Sum                             | 584 a  | 589 b  | 575 b  | 545 b  |
| Current volume (m³ ha⁻¹)        | U      | L      | M      | H      |
| Log                             | 331 b  | 370 a  | 339 b  | 314 b  |
| Pulp                            | 165 a  | 119 b  | 94 b   | 45 c   |
| Wastewood                       | 15 a   | 9 b    | 8 b    | 4 c    |
| Sum                             | 511 a  | 498 b  | 441 b  | 363 a  |
| Thinned volume (m³ ha⁻¹)        | U      | L      | M      | H      |
| Log                             | 7 a    | 7 a    | 25 a   | 56 b   |
| Pulp                            | 13 a   | 51 a   | 72 b   | 93 c   |
| Wastewood                       | 5 a    | 16 b   | 20 b   | 24 c   |
| Sum                             | 25 a   | 74 b   | 117 c  | 173 d  |
| Dead volume (m³ ha⁻¹)           | U      | L      | M      | H      |
| Log                             | 8 a    | 4 a    | 8 a    | 7 a    |
| Pulp                            | 25 a   | 7 b    | 5 b    | 2 b    |
| Wastewood                       | 9 a    | 1 b    | 1 b    | 1 b    |
| Sum                             | 42 a   | 12 b   | 14 b   | 10 b   |
Figure 7. Cumulative volume of dead trees on plots of different thinning intensity: (a) early; (b) medium; (c) late onset of the treatment. For explanation of the symbols, see Figure 2.
unthinned plots, the volume production was only reduced by 4–7 per cent. The results of this study are similar to the results reported in thinning experiments of Norway spruce in other Fennoscandian countries (Möller, 1954; Carbonnier, 1957, 1974; Bryndum, 1967, 1969; Eriksson, 1987; Pettersson, 1993; Eriksson and Karlsson, 1997; Braastad and Tveite, 2000, 2001) and in central Europe (Assmann, 1954; Hamilton, 1976; Schober, 1979, 1980; Kramer and Jünemann, 1985; Spellmann, 1986). In addition, according to the growth and yield tables for Norway spruce developed in Norway (Braastad, 1975), Sweden (Eriksson, 1976), Finland (Vuokila and Väliaho, 1980) and Germany (Assmann and Franz, 1965), total volume production during a stand rotation is not closely related to the thinning intensity. The volume of the trees possibly removed in precommercial thinnings and commercial thinnings carried out before the study was not known. However, the trees removed have no effect on the differences among the treatments.

The results clearly demonstrate that the remaining trees can rapidly occupy the growing space released by the removed trees. The average diameter increment of all trees, as well as that of the largest trees clearly increased (cf. Hamilton, 1976; Abetz and Unfried, 1984; Kramer and Jünemann, 1985; Eriksson, 1987). According to Braastad and Eikeland (1986) and Braastad and Tveite (2001), thinning either did not or only slightly accelerated the growth of the largest trees. Their results were based on delayed and light thinnings and, most probably, the differences in thinning intensity explain these differences.

The treatments had no effect on dominant height increment. On the heavily thinned plots, height increment was slightly faster than that with the other treatments. Thus, the results of this study are in accordance with most studies on Norway spruce, i.e. the height increment of dominant trees is not affected by stand density (cf. Bryndum, 1967; Kramer and Jünemann, 1985; Eriksson, 1987; Handler, 1990; Eriksson and Karlsson, 1997). According to Möller (1954), Bryndum (1969) and Hamilton (1976), height increment may, however, increase with increasing thinning intensity. Those authors have speculated that height growth could be stimulated by the nutrients released from logging residue. On the other hand, reduced height growth on Norway spruce has also been reported after heavy thinning (Abetz, 1976; Abetz and Unfried, 1984).

In this study, the sites of the experiments were fertile and this may contribute to the fast growth of the remaining trees after the release. On less fertile sites, the recovery of the remaining trees may take a longer time and heavy thinnings probably result in larger growth reductions (Mäkinen and Isomäki, 2004a). On the other hand, the treatment onset stage had no major effect on the recovery after the thinning, i.e. slower growing older trees could utilize the free growing space as fast as the trees in younger stands. Even though the medium and late onset stands were dense at the time when the experiments were established, they were not overstocked and the tree crowns were vigorous (Mäkinen and Isomäki, 2004b). Therefore, they were able to rapidly respond to the treatments.

The experiments used in this study were originally planned to study the effects on growth and yield of heavy and seldomly repeated thinnings (Vuokila, 1983). Even though the heaviest thinnings were considered exceptionally intensive at the time of establishment, the results showed that heavier treatments are needed to find out thinning intensities that clearly reduce the total stem volume production. In Norway spruce stands growing on fertile soils, removing even 50 per cent of the growing stock has not resulted in marked reductions in volume increment (Möller, 1954; Carbonnier, 1967; Abetz, 1976; Eriksson and Karlsson, 1997). New thinning experiments that cover the whole stand density range from free-growing trees to unthinned stands are needed in order to define the complete relationship between stand density and volume production.

As was the case for total volume production, merchantable volume produced up to the last measurement was highest on the unthinned and light thinned plots. Only the heavy thinning resulted in a reduced merchantable volume. High stand density may, however, keep tree size under the merchantable limit. Therefore, after a certain stand density level, increasing the stand density may also decrease the total merchantable volume (e.g. Spellmann and Nagel, 1996; Zeide, 2001).
At establishment, the experiments of this study were not completely unthinned. Stand densities on the unthinned plots were probably not high enough to reduce the merchantable volume per hectare.

Even though the differences in total volume production between the unthinned plots and lightly and moderately thinned plots were small, a part of the total production was lost through natural mortality on the unthinned plots. The volume of dead trees was not taken into account when calculating the merchantable volume. In practical forestry, a part of natural mortality may be collected in sanitary cuttings or is still usable at the time of normal harvesting and, thus, the differences in merchantable volume may be somewhat larger. In the earlier measurements, the cause of mortality was not defined and it often remained unclear in the later ones. On the unthinned plots, the main reason was most probably the competition among trees. According to Abetz and Unfried (1984) and Laiho (1987), thinning increases the risk of wind and snow damage for a number of years after the treatment. In contrast, the results of this study indicate no dramatically increased damage risk on thinned plots. However, the plots were rather small and located within a closed stand and, therefore, they do not represent conditions on larger thinned areas.

The differences in basal area per hectare between the thinned stands and their unthinned counterparts have commonly been used as an approximation of competition and suppression in thinned stands (e.g. Pienaar, 1979). Growth after thinning has been related to the basal area remaining in the stand immediately after thinning. In this study, the growth responses to thinning were evaluated against the differences in average basal area between the thinned and unthinned plots during the whole measurement period. The thinning intensity was therefore calculated not only on the basis of the basal area removed in thinnings, but also on the growth response after the thinnings. Thus, the treatments and possible differences in site fertility among the plots may have an effect on average basal area level. In addition, the length of the measurement period varied among the experiments. Period length may not, however, introduce any large bias in the relative differences between the treatments because all the treatments were included in almost all of the experiments.

In those experiments where thinnings were based on the number of stems per hectare, it was soon noticed that the original research plan resulted in a rather similar basal area per hectare, even though the differences in stem number were high. Thus, the original plan was modified and the thinnings were intensified. Furthermore, in some experiments the original schedule could not be completely followed because of high measurement costs, low thinning removals that were not economically viable for the land owner, etc. The same average basal areas were classified into the same group regardless of the thinning schedule, i.e. whether the basal area level was achieved with one intensive thinning or with several light thinnings was not taken into account. All these changes during the long measurement period resulted in different intensities and intervals between successive thinnings, as well as a different number of thinnings. These irregularities may diminish the potential differences between the thinning intensities. At least, the results cannot shed any light on the profitability of few intensive thinnings compared with several light thinnings.

The results are based on experiments on fertile sites in southern Finland. The experimental stands were even-aged and almost pure planted Norway spruce stands with a homogeneous spatial structure. In addition, strip roads were located outside the plots. In southern Finland, the total production loss in Norway spruce stands caused by strip roads at a spacing of 30 m was, on average, 10 m³ ha⁻¹ during the 15-year period after the first commercial thinning (Isomäki and Niemistö, 1990). In practical forestry, the distance between strip roads is nowadays 20 m and most probably results in higher production losses. In this study, the trees were manually felled in random directions and the tree crowns of the felled trees were not directed towards the strip roads as in current mechanized thinnings. Therefore, the nutrients released from logging residues were spatially more evenly distributed. Thus, the results do not completely represent the development of normal commercial forests.

As described above, the material was rather heterogeneous and it had some shortcomings. The long duration of the experiments has caused
technical problems, which became more evident over the course of time. On the other hand, the experimental series used in this study is rare in respect to its extent and duration. Many papers reporting thinning effects are limited to single experiments with a small number of replications and no variation in tree age.

In conclusion, thinning in Norway spruce stands does not increase the total volume increment of trees. The results of this study confirmed the previous Fennoscandian results, based on temporary sample plots, that increasing thinning intensity results in only a small reduction in total stem volume and merchantable volume production within a large range of stand densities. However, the diameter increment of the remaining trees was clearly increased by thinnings. Mean stem diameter of the stand is often used as the criterion of final felling in practical forestry (Hyvänäinen, 2001). Thus, stand rotation can be shortened many years without significant losses in volume yield by applying more intensive management regime (H. Mäkinen, 2004). This study only concentrated on wood production on a cubic metre basis. Whether thinning costs are more than compensated by the income from earlier thinnings remains a topic for further investigation (cf. Valsta, 1982, 1992; Hyytiäinen, 2003).

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