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Thinning of Scots pine and Norway spruce monocultures in Sweden – Effects of different thinning programmes on stand level gross- and net stem volume production

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Abstract

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The effect of thinning intensity, thinning interval, thinning form and timing of the first thinning on stand level gross- and net stem volume production in Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L. Karst) was investigated in a nationwide field experiment across Sweden. In total, 35 Scots pine sites distributed from the south to the north of Sweden and 13 Norway spruce sites located in the south and central parts of Sweden were investigated.

Thinning treatments ranged from unthinned control, to light and moderate repeated thinnings, to a treatment where 60-70% of the basal area was removed in a single thinning. In addition, thinning from above was compared to thinning from below and delayed first thinning was compared to early first thinning. The average measurement period was 31 years for Scots pine and 30 years for Norway spruce. All Scots pine thinning treatments reduced the total gross stem volume production compared to the unthinned control, whereas only the heaviest thinning treatments, in which a large proportion of the basal area was removed, reduced the total gross stem volume production for Norway spruce. Thinning from above did not affect total gross stem volume production of Scots pine, but there was a tendency towards lower production in Norway spruce. For Norway spruce, thinning from above resulted in lower net stem volume production than thinning from below. Delaying the first thinning did not affect gross stem volume production for either Scots pine or Norway spruce. Net volume production and volume production in trees with diameter at breast height > 8 cm was higher for the light thinning treatment than for the unthinned control in Norway spruce. In Scots pine, there was no difference between the light thinning treatment and unthinned control in net volume production. For cots pine, the heavy thinning treatments decreased net volume production compared to the unthinned threatment whereas there were no differences in net volume production between the heavy thinning treatments and unthinned control in Norway spruce.

Key words: *Pinus sylvestris* L., *Picea abies* L. Karst, delayed first thinning, stem volume production, thinning grade, thinning form.

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Contents

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Introduction

For at least two centuries quantifying thinning response employing field experiments has been one of the major goals of growth and yield related research in Europe. An impressive number of thinning experiments have been conducted relating to different tree species, under different site conditions and with different treatment regimes. These experiments have been of great value for describing and understanding stand treatment reactions, as well as for developing thinning guidance for use in operational forestry. Results and conclusions from thinning experiments have been published in the worldwide forest literature. Reviews of the thinning related literature are also available (e.g. Møller, 1954; Braathe, 1957; Assman, 1970; Zeide, 2001; Pretsch, 2004; Wallentin, 2007).

Research on thinning has often been undertaken from a practical perspective. Therefore, the type and intensity of the experimental treatments have often been largely influenced by the prevailing views on thinning in practical forestry. One drawback of this link to practical forestry is that treatments in older experiments often focused on questions relevant to the period during which they were established. For example, thinnings were initiated late in dense stands, thinning intervals were short and thinning from below was the main approach. Older experiments seldom included more extreme thinning treatments. Consequently, results from old experiments may be difficult to apply to modern thinning operations. Another common feature of older experiments is the lack of the application of robust statistical designs. Treatments were often un-replicated, plot sizes were too small and re-measurement protocols were inconsistent over time.

During the 1950s and 60s, European forestry faced a new era, with the rapid mechanisation of forest harvesting operations. Mechanised harvesting methods were applied not only to the final cutting operations, but also to thinnings. Because of this, and for other economic reasons, new thinning programmes with lower initial densities in young stands, increased thinning intensity in young forests, reduced intensity in the later stages of the rotation and longer thinning intervals became more common. The introduction of these new thinning methods raised questions about their effects on long-term forest yield, tree stability and wood quality.

In general, thinning has a negative effect on the total gross stem volume production of a stand. For both Norway spruce and Scots pine, the negative effect has been shown to be correlated to the amount of basal area removed (e.g. Møller, 1952; 1953; 1954; Braathe, 1957; Mäkinen & Isomäki, 2004a; 2004b; Wallentin, 2007). However, it has also been shown that light and moderate thinnings of Norway spruce may increase gross production (Holmsgaard, 1958; Pretzsch, 2004; Judovalkis et al., 2005). Assmann (1970) synthesised the results of old thinning experiments and concluded that the highest growth of “Derbholz” (i.e. volume of stems or branches > 7cm in diameter) was achieved at a somewhat lower basal area than the highest possible level, indicating that thinning could be considered as a tool for enhancing production. Møller (1954) and Braathe (1957) summarised the literature relating to even-aged stands from the first 50-100 years of formal research into the thinning of Norway spruce; their main conclusion was that it is possible to reduce the mean basal area by 50% without any significant decrease in gross volume production. However, as a general rule, and for tree species other than Norway spruce, this conclusion has been subsequently questioned (e.g. Curtis et al., 1997; Zeide, 2001; Skovsgaard, 2009). It is likely that that different tree species react differently to thinning. For Scots pine, Mäkinen and Isomäki (2004a) found that moderate thinning decreased gross stand stem volume production by about 15% and many thinning experiments have similarly reported that volume production decreases with increasing thinning grade and intensity (Pettersson, 1955; Carbonnier, 1959; Wiksten, 1960; Fries, 1961; Eriksson & Karlsson, 1997; Valinger et al., 2000).

The main thinning type in Sweden and Europe during the last 200 years has been thinning from below (Wallentin 2007). Concerns about decreasing growth arising from repeated removal of the largest trees in the stand were raised early in the 20th century (Welander, 1910; Wahlgren, 1914). More recently, there has been discussion about the risk of growth losses due to negative genetic selection after repeated thinning from above (Jäghagen & Albrektsson, 1989). However, production may be increased by thinning from above, since small trees have a higher relative productivity than large trees (Nilsson and Albrektson, 1993).

The timing of the first thinning has a significant impact on the economics of thinning operations (Agestam, 2009). Although delaying first thinning can result in a greater volume of larger sized trees and thus contributing to net-income, the risk of windthrow is increased (Persson, 1975) and hence the practice is not recommended. Experimentally, Mäkinen and Isomäki (2004a) found a small reduction in production associated with late first thinning but they compared experiments on different sites and the results could be partially attributed to random variation. To our knowledge, no study exists that has examined responses to early and late first thinnings in which treatments have been randomly assigned to experimental plots on the same site.

During the 1966-1983 period, a series of field experiments was established to examine thinning and fertilisation in Scots pine and Norway spruce stands throughout Sweden. The original objective of the experiments was to analyse the effects on growth and yield of new thinning treatments including the combined thinning and fertilization treatment. More specific objectives were to analyse the effects on volume growth, stand stability and wood quality of programmes with particularly intensive thinning, repeated thinning from above, thinning in combination with nitrogen fertilisation and thinning in combination with nitrogen and phosphorus fertilisation. One major guiding principle of the new experiments was to use a modern, cost-efficient and consistent experimental design, allowing for proper statistical analysis of data. The experiments were planned to cover an observation period of 50 years or more.

Results from these experiments have been presented in relation to effects on growth and yield (Carbonnier, 1967; Carbonnier & Eriksson, 1970; Eriksson, 1986; 1987; 1990; 1992; Eriksson & Karlsson, 1997), biomass production (Eriksson, 2006), top height growth (Elfving & Kiviste, 1997; Elfving, 2003), canopy density (Johansson, 1986), wind and snow damage (Persson, 1972; Valinger et al., 1994; Valinger & Pettersson, 1996), wood properties (Pape, 1999; Pfister, 2009), fertilisation effects (Persson et al. 1995), single tree volume functions (Karlsson, 1997), stem taper and diameter distributions (Karlsson, 1997; 2005) and rot root (Vollbrecht, 1994).

Based on long-term data from the thinning experiments, this study aimed to evaluate the effects on growth and yield of: (i) thinning intensity; (ii) thinning form; and (iii) the timing of first thinning in Scots pine and Norway spruce stands.

Materials & methods

Description of experimental stands

The experiments were established throughout Sweden during the period 1966-1983 (Table 1; Appendix 1 and 2). The experimental plots were established at the time of first thinning (top height 12-18 m) in uniform, even-aged, pure or almost pure stands of Scots pine or Norway spruce over an 18-year period. Geographically, the Scots pine experiments were located from the county of Skåne in the south of Sweden up to the county of Norbotten in the north (Fig. 1). Norway spruce experiments were only located in southern and central Sweden (Fig. 1).

The development of the stands on different sites varied considerably. In this study, only sites which

Table 1. Description of the experimental sites at the start of the experiment.

				At the start of the experiment			
		No. of sites	**Site index**[ab]	**Basal area (m^2)**	**No. Of stems ha^{-1}**	**Dominant height (m)**	**Age (years)**
Scots pine	**Average**	**35**	25.0	24.4	2172	13.6	40.3
	Min		20.3	17.9	1284	11.9	32.0
	Max		29.7	36.3	3741	15.7	54.0
	Standard dev.		1.99	4.46	572	1.07	6.16
Norway spruce	**Average**	**13**	33.9	33.5	3389	14.3	30.7
	Min		28.2	25.0	1799	11.2	23.0
	Max		38.6	39.0	4966	20.4	45.0
	Standard dev.		2.58	4.49	963	2.20	5.89

[a]Estimated at the last inventories
[b]Dominant height at age 100 years (Hägglund, 1972; 1974)

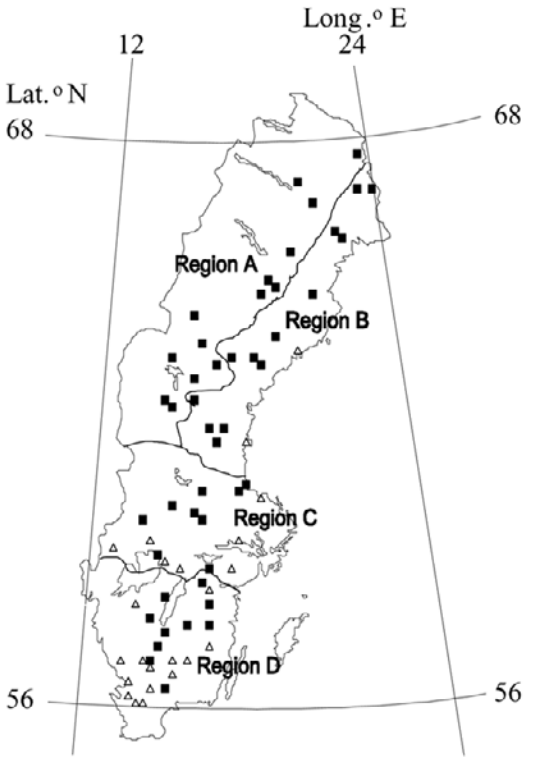

Figure 1. Location of the study sites. Scots pine sites are indicated by a filled square and Norway spruce sites by an open triangle.

had undergone three thinnings and had at least one measurement period after the third thinning were included for Scots pine. For Norway spruce, only sites with four thinnings and at least one measurement period after the fourth thinning were included. These restrictions resulted in 35 out of 47 Scots pine sites and 13 out of 24 Norway spruce sites being included (Table 1; Appendix 1 and 2). The description of the experiments below relates to these 48 sites.

The estimated site index (dominant height at age 100 years, Hägglund, 1972; 1974) averaged 25.0 m for Scots pine and 33.9 m for Norway spruce at the time of the latest re-measurement (Table 1; Appendix 1 and 2). The site indices were in the range 20.3-29.7 m for Scots pine and 28.7-38.6 m for Norway spruce. Thus, the Scots pine sites represent a large part of the fertility gradient found for Scots pine in Sweden whereas the Norway spruce sites represent relatively fertile sites. Basal area at the start of the experiments varied between 17.9 and 36.3 m^2 ha^{-1} (average 23.7 m^2 ha^{-1}) for pine and between 25.0 and 39.0 m^2 ha^{-1} (average 33.5 m^2 ha^{-1}) for Norway spruce (Table 1; Appendix 1 and 2). The average initial dominant height for pine was 13.6 m, ranging from 11.9 to 15.7 m. For Norway spruce, the average initial dominant height was 14.3 m, ranging from 11.2 to 20.4 m (Table 1; Appendix 1 and 2).

Most of the Scots pine stands were established by direct seeding (70%), usually from local seed sources. Six of the 35 stands were established by natural regeneration and four stands were planted (Appendix 1). All but one Norway spruce stand had been regenerated by planting (Appendix 2). Local, as well as central European provenances were used.

Experimental design

The experimental design consisted of one randomised block per site. The size of each treatment unit (measurement plot) was typically 25×40 m (0.1 ha) with a surrounding buffer zone of 10 m. However, the size of the plots sometimes had to be varied due to logistical constraints, but the size of an individual plot was never less than 0.09 ha. Before assigning treatments to the plots, the variation in basal area between plots was checked. The maximum coefficient of variation for basal area was 8%. If variation between plots was greater than this, the plots were rearranged. Consequently, the variation in basal area between plots was relatively small. The treatments were randomly assigned to the plots. The same thinning treatment was used in the buffer zone as in the measurement plot, but the trees in the buffer-zone were not individually numbered as they were in the main plot, in which all trees >45 mm diameter at breast height were permanently numbered.

The thinning treatments represented different thinning grades (percentage of basal area removed), thinning interval, timing of first thinning and thinning type (Table 2). The treatment programmes were tree species- and region-specific (Table 2), with a fixed proportion of the basal area removed at first thinning. In this paper, each thinning treatment is labelled so that the number of thinnings and basal area after thinning are shown. For example, treatment A(3:18) has been thinned three times and the average basal area after each thinning was 18 m^2 ha^{-1}. The letter at the beginning of the treatment label is a code that enables comparison between Scots pine and Norway spruce. Treatment A comprised frequent (3-4), light thinnings, treatment B comprised two heavy thinnings, treatment C comprised a single very heavy thinning, treatment D comprised frequent (3-4) heavy thinnings, treatment E comprised delayed first thinning, treatment F comprised thinning from above,

Table 2. Description of the thinning treatments.

Tree Species	Label	No. of thinnings	Thinning form	Basal area after thinning	Thinning-grade 1:a thinning [a]	Comment	Number of sites [c] Total	In this study
Scots pine								
	A(3:18)	3-4	Below	18	25		47	35
	B(2:15)	2	Below	15	43		19	15
	C(1:10)	1	Below	10	60-63		48	35
	D(3:13)	3-4	Below	13	50		18	15
	E(2:18)D	2-3	Below	18	Varying[b]	Delayed first thinning	26	20
	F(3:18)A	3-4	Above	18	20-25	Thinning from above	48	35
	I(0:0)	0					49	35
Norway spruce								
	A(4:28)	4-6	Below	28	20-25		20	13
	B(2:23)	2-3	Below	23	40-43		17	13
	C(1:12)	1	Below	12	63-70		19	13
	D(4:20)	4-6	Below	20	40-50		16	9
	E(3:28)D	3-5	Below	28	Varying[b]	Delayed first thinning	15	12
	F(4:28)A	4-6	Above	28	20	Thinning from above	16	9
	I(0:0)	0					24	13

[a]The thinning grade is per cent removed basal area of the basal area before thinning

[b]Treatment E was thinned to the same basal area after thinning as treatment A

[c]Number of sites refers to number of experiments containing a specific treatment. Only sites which had undergone three thinnings and had at least one measurement period after the third thinning were included for Scots pine. For Norway spruce, only sites with four thinnings and at least one measurement period after the fourth thinning were included

and treatment I was the unthinned control.

The thinning grade was determined on the basis of the percentage of basal area removed in the first thinning (Table 2). For treatment A, the thinning grade was about 20-25%, for treatments B and D it was 40-50% and for treatment C it was 60-70%. Because of this, the basal area after thinning varied considerably between sites for a specific treatment depending on the variation in basal area before thinning (Table 1; Appendix 3). In subsequent thinnings, the basal area after thinning in treatment A and D increased by 0.2 % per year, and consequently almost all growth between any two thinnings was removed during the later thinning. Treatment B was aimed at keeping the average basal area over the whole thinning period at the same level as treatment A (Figure 2). All thinnings were done with a chain saw and the trees were carried out of the plots in order to avoid damage from logging machines on trees and soil.

The interval between thinnings was determined on the basis of dominant height. Between the thinnings, the dominant height should have increased by a predefined value (Table 3). The prescribed increase in dominant height between thinnings was different for Scots pine and Norway spruce and between northern and southern Sweden for Scots pine (Table 3).

The first thinning was performed at a dominant height of 11.9-15.6 m for Scots pine and 12.8-20.2 m for Norway spruce (Fig. 3; Appendix 1-2). The delayed first thinning was conducted after an increase in the dominant height of 2.2-3 m, equating to a dominant height of 15.3-18.9 m for Scots pine and 15.2-23.9 m for Norway spruce. For Scots pine, the basal area before thinning varied between 17.8 and 36.3 m^2 ha^{-1} and was, on average, 24.4 m^2 ha^{-1}. Basal area for the delayed first thinning treatment varied between 23.6 and 47.9 m^2 ha^{-1}. For Norway spruce, basal area before thinning varied between 25.0 and 39.0 m^2 ha^{-1} for the normal timing of first thinning and 36.1-52.9 m^2 ha^{-1} for the delayed first thinning (Fig 3; Appendix 1-2).

Two different thinning types were compared. In thinning from below, trees were removed in all diameter classes but more frequently from the smaller sizes, thus resulting in the mean diameter quotient between removed and retained trees being 0.70-0.90. For treatment F (thinning from above), trees in the dominant tree-classes were removed preferentially during thinnings, providing space for smaller, well developed trees. The thinning ratio had to be above 1.0 and the thinning ratio at the first thinning was intended to be above 1.15. No living trees with a diameter at breast height below 10 cm were removed when thinning from above. The thinning ratio was

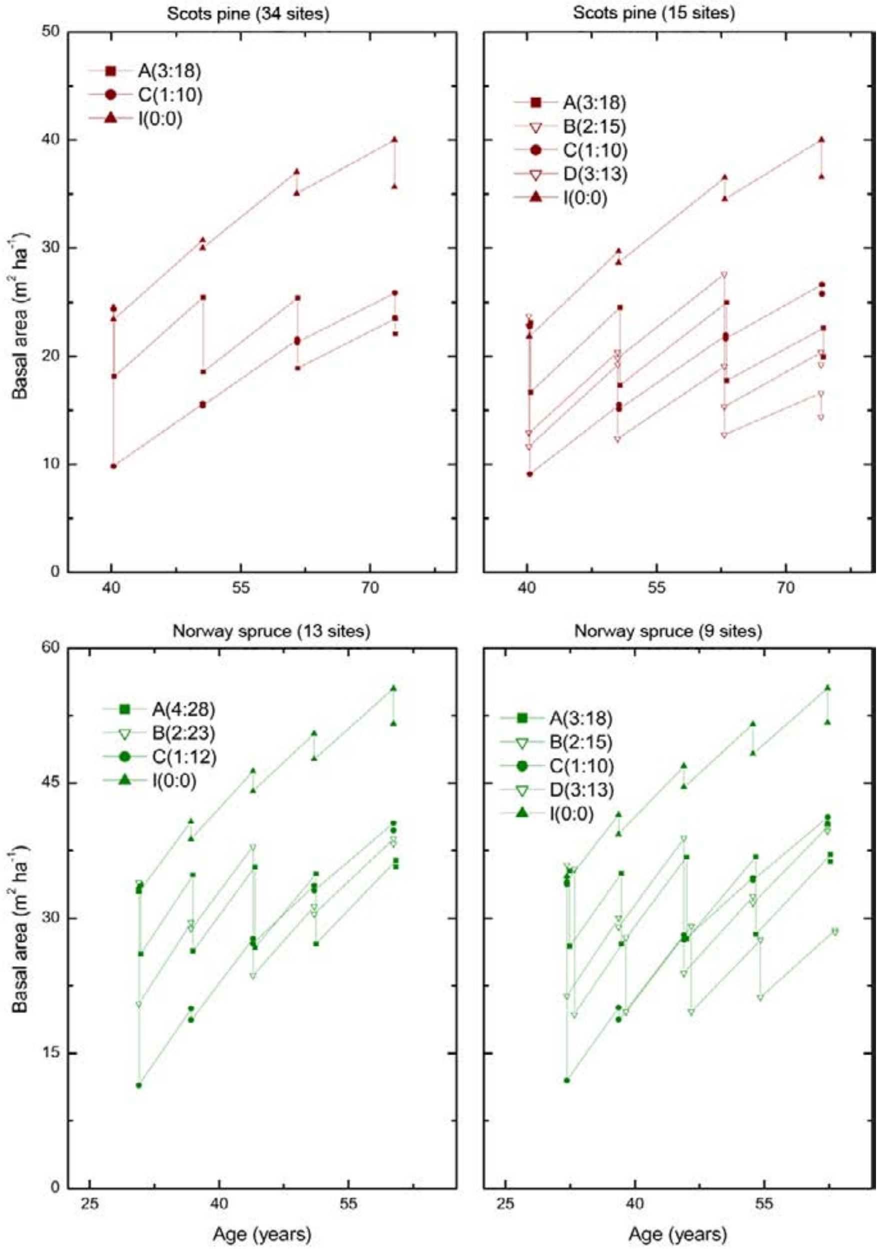

Figure 2. Development of average basal area for the various thinning treatments in Scots pine (top) and Norway spruce (bottom). Average values for the large data set (left) and small data set (right).

Table 3. Height growth of dominant trees between thinnings.

	Height growth between thinnings (m)		
	Norway spruce	Scots pine	
		Southern S.	Northern S.
1:st thinning - 2:nd thinning	3.0	3.0	2.8
2:nd thinning - 3:rd thinning	2.8	2.7	2.2
3:rd thinning - 4:th thinning	2.5		

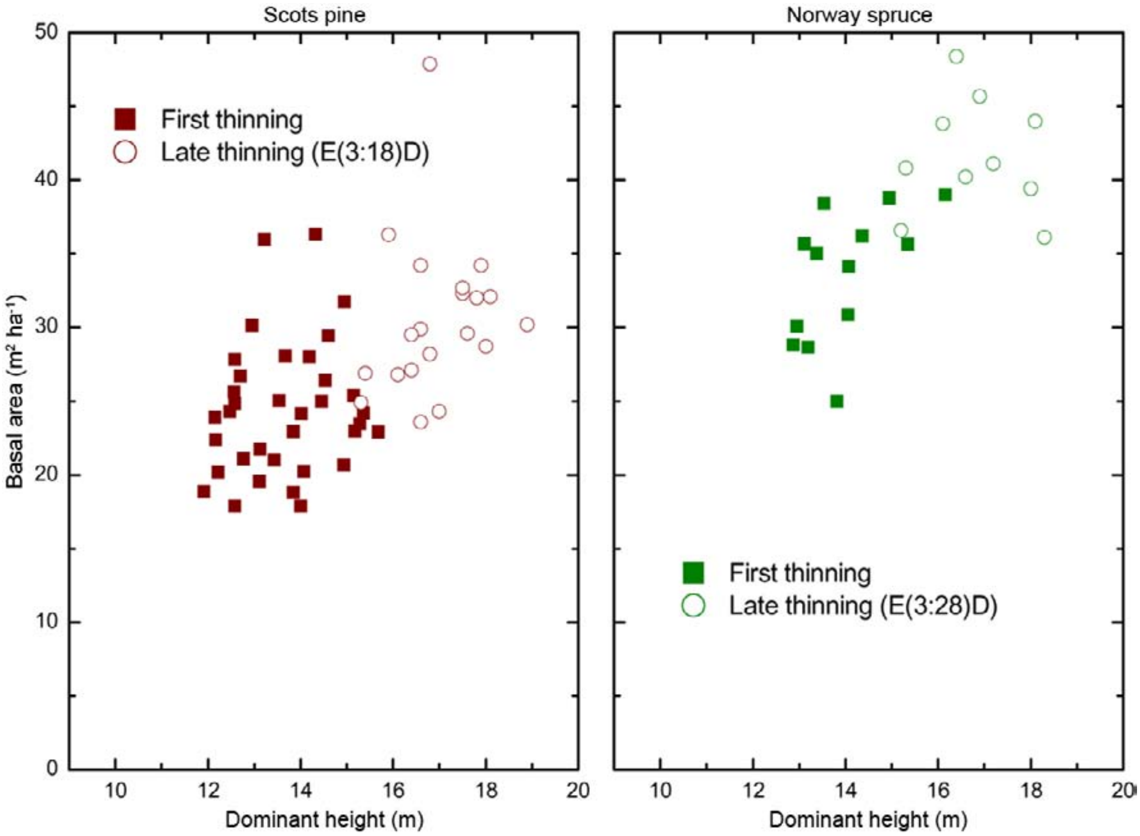

Figure 3. Dominant height and average basal area for the experimental sites at the time of first thinning and at the time of late in treatment E.

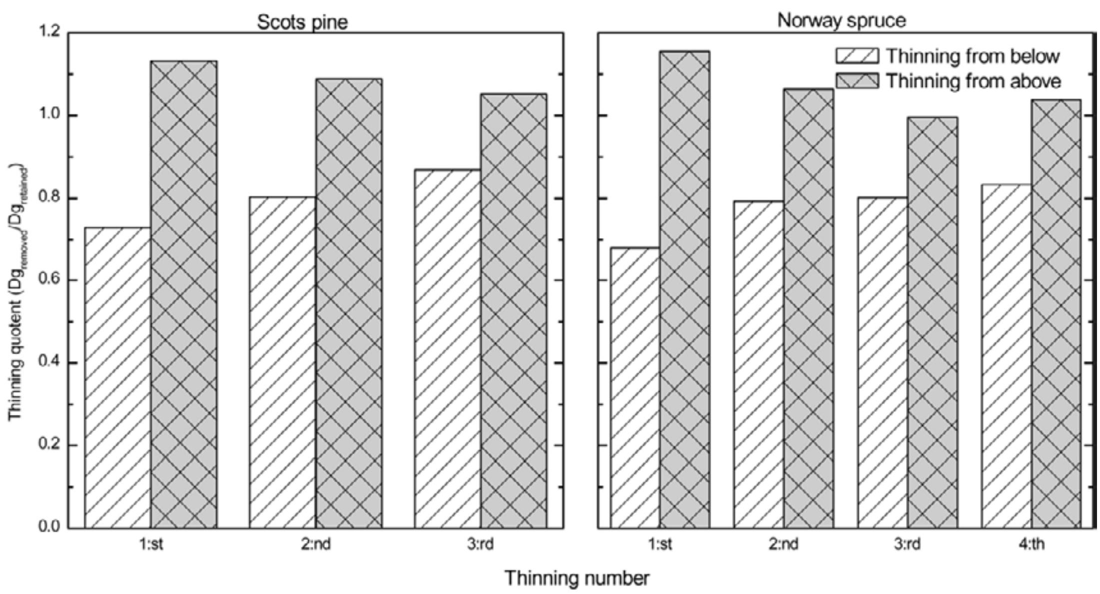

Figure 4. Thinning quotient ($Dg_{removed}/Dg_{retained}$) for thinning from below and thinning from above in the first–third thinnings for Scots pine (left) and first–fourth thinnings for Norway spruce (right).

lowest at first thinning and increased slowly in subsequent thinnings for thinning from below, whilst the opposite was true for thinning from above (Fig. 4). Irrespective of thinning type, trees with low vitality and severe damage were removed whenever possible during thinning. The aim was an even spatial distribution of healthy residual stems. Species of trees other than the main species were also removed at first thinning if possible. The thinning programme was abandoned if the density of the remaining stand reached the pre-determined treatment-specific levels (300-350 trees ha^{-1} for Norway spruce and 300-400 trees ha^{-1} for Scots pine.

One block was established on each site but not all treatments were represented at all sites (Table 1; Appendix 1-2). For Scots pine, treatments A(3:18), C(1:10), F(3:18)A and I(0:0) were represented at all 35 sites while the other treatments were represented at varying frequencies. Treatments B(2:15) and D(3:13) were only present at sites in southern Sweden (Appendix 1). For Norway spruce, treatments A(4:28), B(2:23), C(1:12) and I(0:0) were represented on all 13 sites used in this study.

Measurements

The diameter at breast height (130 cm above ground; DBH) was recorded for all trees at the start of the experiment, at the time of every thinning and at irregular times between the thinnings. The diameter was measured, using callipers, in two perpendicular directions and recorded to the nearest mm. The calliper position on the stem was permanently marked to ensure that it did not vary between measurements. At the same time, tree species, status (retained, removed, missing, wind-felled) and tree properties (crown performance, physical damage, vitality) were recorded. In addition to diameter, tree-height (H), height to the living crown (HL) and thickness of the bark (B1, B2) were recorded for systematically selected sample trees within the plots. Tree-height and height to the living crown were recorded with an accuracy of about 0.1-0.2 m and the thickness of the bark with an accuracy of about 0.1 mm. Two separate groups of sample trees were selected, one among the retained and one among the removed trees. Among the retained trees, separate sample trees were selected from the 100 trees per hectare with the largest diameter. Among both the retained and the removed trees, sample trees were selected at a fixed quotient (Karlsson 1998). This sampling procedure resulted in a higher proportion of sample trees that were large (Fig 5). For Scots pine, the sample tree ratio (the proportion of sample trees in relation to the total number of trees) was higher at the time of the first measurements (about 45%) than during later measurements (about 23%). For Norway spruce, the

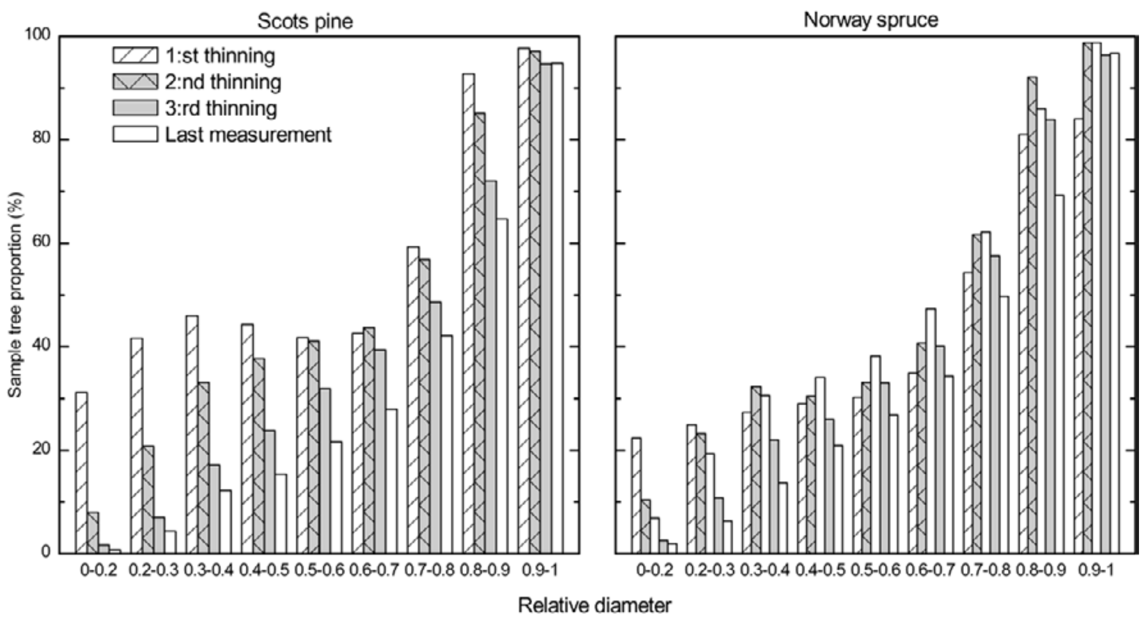

Figure 5. Sample tree proportion in relative diameter classes (total of trees sampled relative the total number of trees on the plots, by relative diameter class). The first relative diameter class contained the 20% representing the smallest trees; all other relative diameter classes contain 10% of the trees.

sample tree ratio was relatively constant throughout the experimental period (27-37%) (Fig. 5). The same sample trees were retained for the whole experimental period when possible, but after thinning and due to mortality some sample trees had to be replaced. Furthermore, trees with damage that affected height and/or diameter development were not chosen as sample trees.

Damage and the cause of damage were recorded for all trees on all measurement occasions (Table 4). Due to computer limitations at the time of the early measurements, only three different causes of damage could be recorded for each tree. If more than three types of damage were present on an individual tree, these were prioritised according to Table 4. In addition to the causes of damage that are represented in Table 4, wind-throw and missing trees were recorded separately.

Calculations

Stem-volumes of sample trees were calculated with functions developed by Brandel (1990) using diameter at breast height (DBH), height (H) and height to the first living branch (HL) for Norway spruce and DBH, H, HL and thickness of the bark (B) for Scots pine as independent variables. Different functions were used for northern and southern Sweden. Thereafter, the volume of all callipered trees was estimated using a method based on the assumption that there is a linear relationship within a stand between basal area at breast height and tree volume, and consequently between D^2 and tree volume also. This assumption is based on previous results presented by Hummel (1955). The following steps describe how the total stem volume calculation for a species category (retained, removed, and dead) was carried out:

Stem volume of the sample trees was estimated using an appropriate volume function for individual trees. The sample trees were grouped into DBH-classes of 2 cm. The following calculations were carried out for all diameter-classes: Number of sample trees (Ncp); sum of squared diameters (Dcp); sum of volumes (Vcp); mean squared diameters (Dmcp), Dmcp = Dcp/Ncp; mean volume (Vmcp), Vmcp = Vcp/Ncp.

All callipered stems on the plot were also grouped into DBH-classes analogous to the sample-tree DBH-classes. The following calculations were carried out for the classes represented: Number of stems (N_{cs});

Table 4. Causes of damage that were recorded for all callipered trees. A maximum of three different causes of damage were recorded per tree; damage was recorded according to the order of ranking if more than three sources of damage were found on a particular tree.

Rank	Cause of damage in order of ranking
1	Dry and/or felled tree
2	Stem breakage (under living crown, within the lower half of living crown, in the upper half of the living crown)
3	Dry top (>5dm, 2-5 dm, <2 dm)
4	Deformed diameter at breast height
5	Stem wound (1/4, 1/8-1/4, >1/4 of the circumference)
6	Peridermium (more than half of circumference, less than half of circumference)
7	Drying tree (expected to die within five years)
8	Leaning trees
9	Damaged by fungi or insects so growth or value are affected
10	Canker (more than half of circumference, less than half of circumference)
11	Root-rot (only if fruiting-body or rotted wood can be seen)
12	Spike knot (Root-section, middle section, top section)
13	Bend, large dry branches or other variables causing down grading of logs
14	Suppressed tree
15	Wolf-type tree (large, dominating tree with bad quality)

sum of squared diameters (D_{cs}); mean squared diameters (D_{mcs}), $D_{mcs} = D_{cs}/N_{cs}$.

The mean volume in a DBH-class (V_{cmean}) was calculated by $V_{cmean} = V_{mcp}*D_{mcs} / D_{mcp}$. The total volume of a diameter class (V_{ctot}) was calculated by $V_{ctot} = V_{cmean}*N_{cs}$. If sample trees were missing from a class where one or more callipered trees were present, V_{cmean} was calculated by the formula $V_{cmean} = V_{mcp}*D_{mcs} / D_{mcp}$, using V_{mcp} and D_{mcp} from the nearest class containing at least one sample tree.

The calculations described above were repeated for all diameter-classes and species and categories represented within a sample plot. Separate calculations were carried out for the groups retained, removed and dead trees, respectively. The volume estimates for the dead trees were based on the sample trees in the category removed trees where such trees were available. If not available, it was based on the retained trees.

Top height for each plot by measurement occasion was estimated by the height-curve developed by Näslund (1936):

$$H=D^x/(a+bDBH)^x + 1.3 \qquad (1)$$

where H=tree height (m); DBH=diameter at breast height (cm); a and b are coefficients and x has a value of 2 for Scots pine and 3 for Norway spruce (Pettersson 1955). Thereafter, the top height was estimated by use of the height function, as the height corresponding to the arithmetic mean diameter of the 100 trees with the greatest DBH per hectare. The number of trees per plot for estimating top height was about 5-10. Site index (SI) was determined from species-specific site index curves (Hägglund 1972; 1973; 1974).

Comparisons between treatments were conducted on the basis of three predefined categories (Table 5). First, the effect of thinning-grade and interval between thinning was compared for treatments A, B, C and D. Secondly, the timing of first thinning was compared for treatments A and E. Finally, the thinning-form was compared for treatments A and F. For all three comparisons, the untreated control treatment (I) was included (Table 5).

Volume is reported as gross- and net volume production from the first thinning until last measurement. In net volume production, the volumes of self-thinned trees, missing trees and wind-felled trees are subtracted from gross-volume production. In addition, volume production is reported for trees exceeding 8 cm in diameter at breast height when harvested in thinnings or retained until the last measurement.

The SAS general linear model (Anon 1998) was used to perform statistical tests. The following model was used:

$$Y_{ij}=m+A_i+B_j+e_{ij} \qquad (2)$$

where A_i=effects of site (block) and B_j=effects of thinning treatments.

Differences between thinning treatments were evaluated for predefined categories using LSD mean separation tests following analysis of variance ($p<0.05$).

In addition to the above comparisons, relative growth of the thinned plots was correlated to a number of independent variables. Relative growth rate was defined as the ratio between growth of a thinned plot and the unthinned control on the same site. Among other comparisons, relative growth rates were correlated to average basal area BA_a and relative basal area RBA_a. The average basal area was calculated by:

$$BA = \sum_{i=1}^{n-1} \frac{Ti(BAr(i) + BAt(i+1))/2}{Ttot} \qquad (3)$$

Table 5. Planned comparisons in the analysis of variance and number of sites for each comparison.

Planned comparisons	Tree species	Treatment					No. of sites
Thinning grade and thinning intervals	Scots pine	A(3:18)	C(1:10)	I(0:0)			35
	Scots pine	A(3:18)	B(2:15)	C(1:10)	D(3:13)	I(0:0)	15
	Norway spruce	A(4:28)	B(2:23)	C(1:12)	I(0:0)		13
	Norway spruce	A(4:28)	B(2:23)	C(1:12)	D(4:20)	I(0:0)	9
Thinning form	Scots pine	A(3:18)	F(3:18)A	I(0:0)			35
	Norway spruce	A(4:28)	F(4:28)A	I(0:0)			9
Timing of first thinning	Scots pine	A(3:18)	E(2:18)D	I(0:0)			20
	Norway spruce	A(4:28)	E(3:28)D	I(0:0)			12

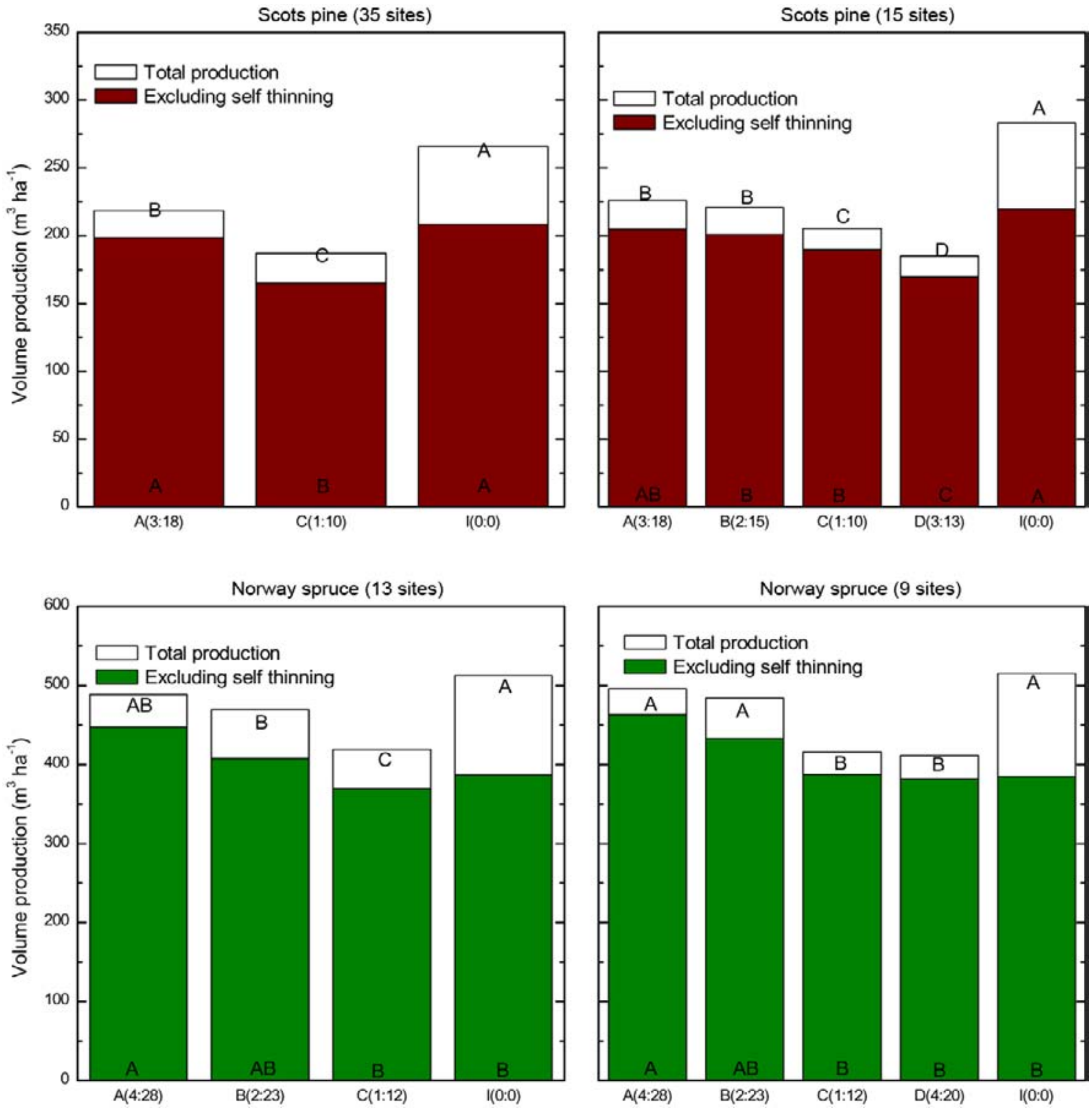

Figure 6. Volume production (m^3 ha^{-1}) for the period between first thinning and final data collection for treatments with different thinning intensities and different intervals between thinnings. The entire bar represents volume production including self thinning and the lower, shaded part of each bar represents net volume production (volume production excluding self thinning). Significant differences between treatments at the 5% probability level are indicated by different letters.

where: BAr is the basal area of the retained living trees at the beginning of each measurement period; BAt is the total basal area at the end of each measurement period, including dead trees and trees to be thinned; T*i* is the length of each measurement period (years); Ttot is the length of the total measurement period; and n is the number of measurement periods. Relative basal area (RBA_a) was defined as the ratio between the average basal area (BA_a) of thinned plots and the BA_a of unthinned control plots at the same site.

Results

Thinning grade and interval between thinnings

Total stem-volume production from first thinning until the final measurement was evaluated for one large and one small data set each for Scots pine and Norway spruce (Table 5). Total production was highest for the unthinned control treatments for both Scots pine and Norway spruce (Fig 6). For the large Scots pine data set, the unthinned control exhibited

Table 6. Current annual increment (CAI, m^3 ha^{-1} $year^{-1}$), including self tinning (gross CAI) and excluding self thinning (net CAI) volumes, for the various thinning treatments for Scots pine (top) and Norway spruce (bottom) experiments. Average values for one large data set and one smaller data set are shown for both Scots pine and Norway spruce. Gross- and net-CAI is shown for three periods for Scots pine and four periods for Norway spruce. The growth periods occur between the thinning occasions in treatment A and between the final thinning and the final measurement. Statistically significant differences among treatment means are indicated by different letters.

	Including self thinning			Excluding self thinning		
	1:st-2:nd	2:nd-3:rd	3:rd-last	1:st-2:nd	2:nd-3:rd	3:rd-last
Scots pine (35 sites)						
A(3:18)	7.7 B	7.2 B	6.4 B	7.5 B	6.6 B	5.4 A
C(1:10)	5.3 C	6.6 C	6.3 B	5.1 C	6.4 B	4.8 A
I(0:0)	8.4 A	8.8 A	8.5 A	8.0 A	7.3 A	5.2 A
Scots pine (15 sites)						
A(3:18)	7.7 A	7.2 B	6.0 C	7.2 A	6.7 AB	4.8 BC
B(2:15)	6.7 B	7.6 B	5.9 C	6.3 B	7.4 B	4.8 BC
C(1:10)	5.7 C	6.5 C	6.8 B	5.3 C	6.3 BC	5.9 A
D(3:13)	6.5 B	5.8 D	4.6 D	6.2 B	5.7 C	4.1 C
I(0:0)	8.2 A	8.7 A	8.7 A	7.4 A	7.3 A	5.4 B

significantly higher production than either A(3:18) or C(1:10). For Norway spruce, the unthinned control exhibited significantly higher production than either B(2:23) or C(1:12) for the large data set and D(4:20) or C(1:12) for the small data set. For both Scots pine and Norway spruce, the single heavy thinning (C) and repeated heavy thinnings (D) resulted in significantly lower total production than the treatments involving many light thinnings (A) and few heavy thinnings (B) (Fig 6).

Net stem volume production, stem-volume production excluding self-thinning, was significantly lower for C(1:10) then for A(3:18) and I(0:0) in Scots pine (Fig 6). For the small data set, the heavy thinning D(3:13) had lower stem-volume production than all other treatments. For Norway spruce, production excluding self-thinning was significantly higher for A(4:28) than for the unthinned control, while the heavy thinnings (C and D) were not significantly different compared to the unthinned control but did result in significantly lower net production compared to treatment A(4:28).

Current annual stem-volume increment (CAI) for Scots pine was significantly higher for the unthinned control than for other treatments during all three periods (Table 6). For Norway spruce, CAI for the unthinned control was only significantly higher than the heavily thinned treatments (C(1:12) and D(4:20)). The single heavy thinning resulted in significantly reduced CAI during the early periods for both Scots pine and Norway spruce, but during the final period it was not significantly lower than for the light thinnings (A and B). Heavy, repeated thinnings (D) resulted in a gradual decrease in CAI compared to the other treatments (Table 6).

Net current annual stand stem volume production (Net CAI, current annual stem volume increment excluding self-thinning) in Scots pine was highest for unthinned plots during the first two periods but not during the third (Table 6). During the last period, from third thinning until the final measurement, there was no significant difference in net-CAI between any of the thinning treatments for Scots pine. For Norway spruce, net-CAI was significantly lower for the unthinned control than for repeated light thinnings (A4:28)) during the second and third period. As for Scots pine, the single heavy thinning resulted in low CAI compared to the other treatments during the early periods but not during the final one. In addition, net-CAI for the heavy, frequent thinning treatment (D(4:20) decreased with time (Table 6).

Thinning effects on individual tree size

Average diameter according to basal area (D_{BA}) at

Table 7. Average diameter according to basal area (D_{BA}) of trees removed during thinnings and for the remaining trees at the time of the final measurement. In addition, the average D_{BA} values for all trees including trees removed during thinnings and trees remaining at the time of the final measurement are shown. Statistically significant differences among treatment means are indicated by different letters.

Scots pine

	35 sites					15 sites				
	1:st	2:nd	3:rd	Last	Total	1:st	2:nd	3:rd	Last	Total
A(3:18)	10.0 B	14.0	18.7	23.6 B	16.5 C	9.5 B	14.6 A	20.0 B	24.7 A	17.4 C
B(2:15)						10.1 AB		19.4 B	26.3 A	18.8 B
C(1:10)	11.0 A	.	.	24.8 A	17.9 B	10.7 A			26.0 A	18.4 B
D(3:13)						10.2 AB	15.9 A	22.6 A	25.4 A	18.6 B
I(0:0)				19.6 C	19.6 A				20.7 B	21.3 A

Norway spruce

	13 sites						9 sites					
	1:st	2:nd	3:rd	4:th	Last	Total	1:st	2:nd	3:rd	4:th	Last	Total
A(4:28)	8.9 C	12.8	16.0 A	19.9	28.0 B	17.2 C	8.8 B	12.3 B	15.6 B	19.6 B	27.7 B	16.9 C
B(2:23)	9.7 B		16.9 A		28.4 B	18.3 B	9.7 A		16.7 B		28.7 B	18.4 BC
C(1:12)	10.3 A				30.7 A	20.5 A	10.1 A				29.7 B	19.9 AB
D(4:20)							10.0 A	14.9 A	19.6 A	26.1 A	34.7 A	21.2 A
I(0:0)					20.7 C	20.7 A					20.8 C	20.8 A

the time of the final measurement was significantly lower for the unthinned control than for thinned plots for both Scots pine and Norway spruce (Table 7). For Scots pine, there was little difference between thinning treatments with respect to D_{BA} at the time of the final measurement; treatment C(1:10) had a significantly higher D_{BA} than A(3:18) but the absolute difference was small (Table 7). For Norway spruce, the extra heavy thinning treatment (D(4:20)) resulted in a significantly higher D_{BA} at the time of the final measurement than for the other thinning treatments but there were no statistically significantly differences between the other thinning treatments. The D_{BA} for all stems removed during thinning and the retained stems at the time of the final measurements was significantly larger in the unthinned control than in the thinned plots for Scots pine. For Norway spruce, D_{BA} of all stems was significantly higher in the unthinned than in the light thinning treatments (A(4:28) and B(2:23)) but not compared to the heavy thinning treatments (C(1:12) and D(4:20)) (Table 7). For both Scots pine and Norway spruce, the light thinning treatment (A) resulted in lower total D_{BA} of all removed stems than the heavy thinning treatments (C and D) (Table 7).

Volume in trees with diameter at breast height above 8 cm was significantly lower for the heavy thinning treatments (D(3:13)) and C(1:10) than for the unthinned treatment and it was significantly lower for D(3:13) than for A(3:18) in Scots pine (Fig 7). For Norway spruce, volume in trees with DBH>8 cm was lower in the heavy thinning treatments (D and C) and in the unthinned control than in the light, frequent thinning treatment (A(4:28)) (Fig 7). The proportion of volume removed during thinnings was highest in the D-treatment for both Scots pine and Norway spruce (51% and 47%, respectively). For Scots pine, a larger proportion of the total merchantable volume was removed during thinnings for the B-treatment than for the A-treatment while the opposite was true for Norway spruce. For both Scots pine and Norway spruce, the lowest proportion of merchantable volume in thinnings was in the single thinning treatment (25% and 21% for Scots pine and Norway spruce, respectively).

Delayed first thinning

Delaying first thinning did not affect total production for either Scots pine or Norway spruce (Fig 8). For Scots pine, the total production of thinned treatments (A and E) was significantly lower than for the unthinned control, while there was no significant

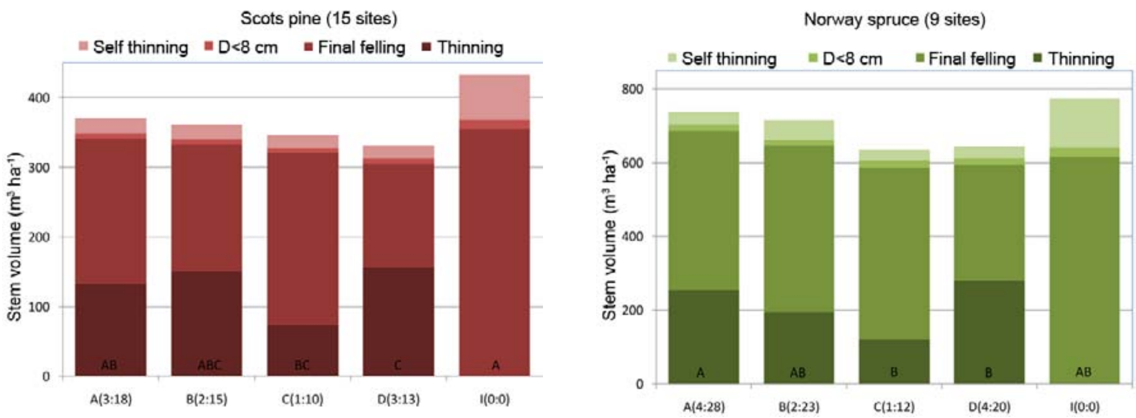

Figure 7. Volume production (m[3] ha[-1]) divided into volume removed during thinnings for trees with diameter at breast height (DBH) above and below 8 cm; volume of trees remaining at the time of the final measurement and volume of self-thinned trees for treatments with different thinning intensities and different intervals between thinnings. Significant differences between treatments with respect to merchantable timber volume (the first two groups) at the 5% probability level are indicated by different letters.

difference between thinned and unthinned treatments for Norway spruce. For Scots pine, net production was the same for all three treatments, whereas for Norway spruce, the thinned plots exhibited significantly higher production exclusive of self-thinning than the unthinned control (Fig 8).

Delayed thinning did not significantly affect gross current annual increment (gross-CAI) for either Scots pine or Norway spruce (Table 8). In the second period (between the second and third thinnings) gross- and

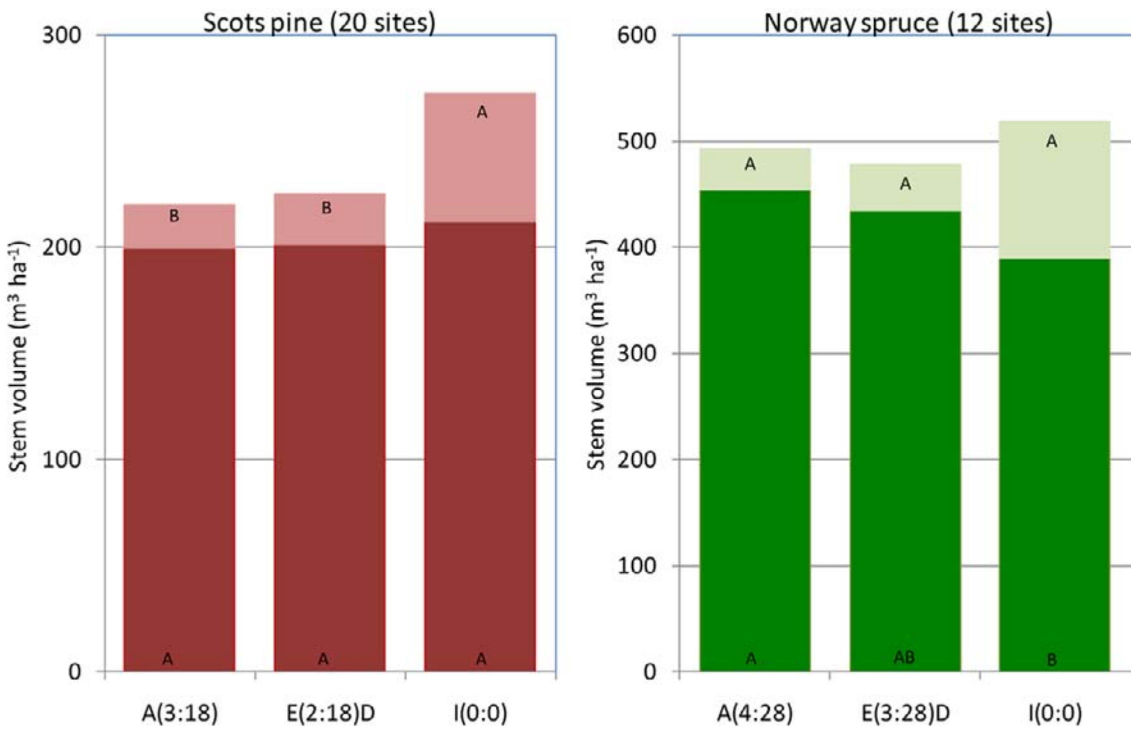

Figure 8. Volume production (m[3] ha[-1]) for the period between first thinning and final data collection for delayed first thinning (E) compared to earlier first thinning (A) and the unthinned control (I) for Scots pine (left) and Norway spruce (right). The entire bar represents volume production including self-thinning and the lower, shaded part of each bar represents net volume production (volume production excluding self thinning). Significant differences between treatments with respect to total production (top parts of the bars) and production excluding self-thinning (bottom parts of the bars) at the 5% probability level are indicated by different letters.

Table 8. Current annual increment (m³ ha⁻¹), including self tinning (gross CAI) and excluding self thinning (net CAI), for delayed first thinning (E) compared to earlier first thinning (A) and the unthinned control (I) for Scots pine (top) and Norway spruce (bottom) experiments. Gross- and net-CAI is shown for three periods for Scots pine and four periods for Norway spruce. The growth periods were between the thinning occasions in treatment A and between the final thinning and the final measurement. Statistically significant differences among treatment means are indicated by different letters.

Scots pine	Including self thinning			Excluding self thinning		
	1:st-2:nd	2:nd-3:rd	3:rd-last	1:st-2:nd	2:nd-3:rd	3:rd-last
Scots pine (20 sites)						
A(3:18)	7.3 B	7.2 B	6.1 B	7.3 A	6.8 B	5.1 A
E(2:18)D	8.4 A	7.3 B	5.8 B	7.9 A	6.8 B	4.7 A
I(0:0)	8.4 A	8.9 A	8.3 A	7.9 A	7.7 A	4.9 A

Norway spruce	Including self thinning				Excluding self thinning			
	1:st-2:nd	2:nd-3:rd	3:rd-4th	4th-last	1:st-2:nd	2:nd-3:rd	3:rd-last	4th-last
Norway spruce (12 sites)								
A(4:28)	18.1 A	17.8 A	17.0 A	16.7 AB	17.2 A	17.6 A	17.0 A	14.1 A
E(3:28)D	18.4 A	17.3 A	17.0 A	15.5 B	16.8 A	16.8 AB	17.0 A	13.4 AB
I(0:0)	18.2 A	17.5 A	18.3 A	18.7 A	16.1 A	14.9 B	14.3 B	11.3 B

net CAI was almost identical for the A- and E-treatments in Scots pine and only marginally lower, but not significantly so, for E than A in Norway spruce. During the final period late thinning resulted in lower CAI than the unthinned control for Norway spruce whereas the difference between the frequent and light thinning treatment (A) and the unthinned control was not statistically significant (Table 8). Self thinning in the A- and E-treatments was almost identical for both Scots pine and Norway spruce. Therefore, net-CAI showed the same pattern as gross-CAI (Table 8).

Because the late thinning treatment (E) was thinned down to the same basal area as the normal

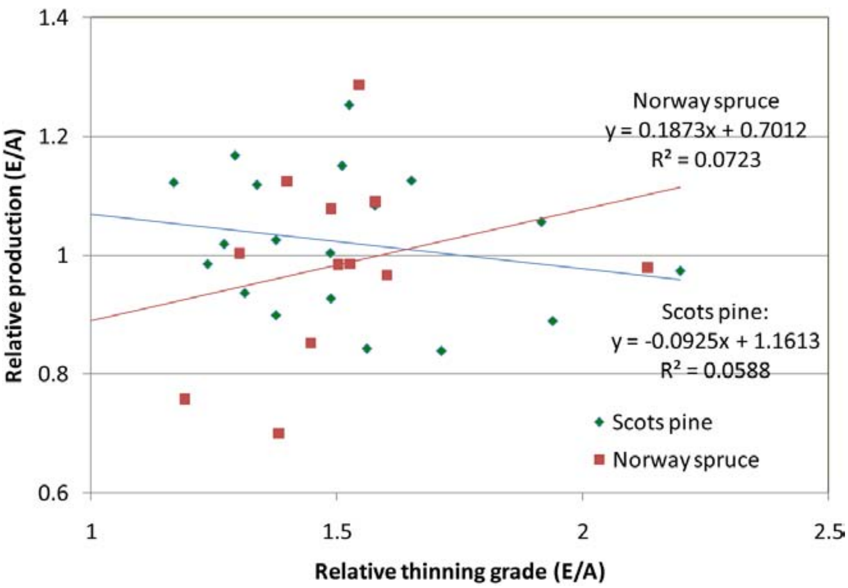

Figure 9. Production of the delayed thinning treatment (E) in relation to production of the thinning treatment with one earlier thinning (A) at the same site. Relative production values below one indicate lower production in treatment E than treatment A. Relative production is shown over relative thinning grade (removed basal area/ basal area before thinning). Relative thinning grade is the ratio between thinning grades for treatment E and A on the same site. A relative thinning grade above one indicates a higher thinning grade for treatment E than A.

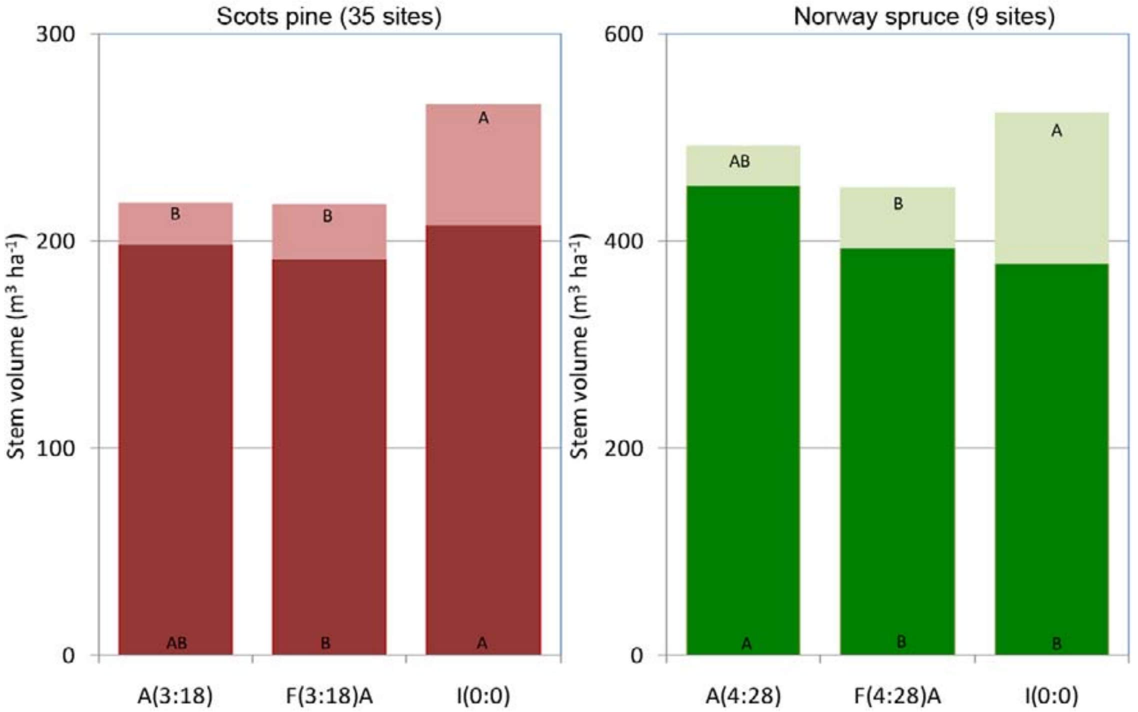

Figure 10. Volume production (m^3 ha^{-1}) for the period between first thinning and final data collection for thinning from above (F) compared to thinning from below (A) and the unthinned control (I) for Scots pine (left) and Norway spruce (right). The entire bar represents volume production including self-thinning and the lower, shaded part of each bar represents net volume production (volume production excluding self thinning). Significant differences between treatments with respect to total production (top part of the bars) and production excluding self-thinning (bottom part of the bars) at the 5% probability level are indicated by different letters.

Table 9. Current annual increment (m^3 ha^{-1}), including self tinning (gross CAI) and excluding self thinning (net CAI), for thinning from above (F) compared to thinning from below (A) and the unthinned control (I) for Scots pine (top) and Norway spruce (bottom) experiments. Gross- and net-CAI is shown for three periods for Scots pine and four periods for Norway spruce. The growth periods were between the thinning occasions in treatment A and between the final thinning and the final measurement. Statistically significant differences among treatment means are indicated by different letters.

Scots pine						
	Including self thinning			**Excluding self thinning**		
	1:st-2:nd	**2:nd-3:rd**	**3:rd-last**	**1:st-2:nd**	**2:nd-3:rd**	**3:rd-last**
Scots pine (20 sites)						
A(3:18)	7.7 B	7.2 B	6.4 B	7.5 B	6.6 B	5.4 A
F(3:18)A	7.4 B	7.2 B	6.5 B	7.0 C	6.3 B	5.5 A
I(0:0)	8.4 A	8.8 A	8.5 A	8.0 A	7.3 A	5.2 A

Norway spruce								
	Including self thinning				**Excluding self thinning**			
	1:st-2:nd	**2:nd-3:rd**	**3:rd-4th**	**4th-last**	**1:st-2:nd**	**2:nd-3:rd**	**3:rd-last**	**4th-last**
Norway spruce (12 sites)								
A(4:28)	17.6 A	17.6 A	17.2 AB	16.1 AB	16.4 A	17.6 A	16.6 A	13.5 A
F(4:28)A	17.0 A	15.5 B	15.7 B	14.4 B	15.5 A	14.3 B	14.1 B	11.8 AB
I(0:0)	18.1 A	16.9 AB	17.8 A	17.5 A	15.7 A	14.4 B	14.4 B	10.2 B

thinning treatment (A), the proportion of basal area removed at thinning was greater for E than A. On average for Scots pine, the thinning grade (removed basal area as a percentage of basal area before thinning) was 49% greater for treatment E(2:18)D than for A(3:18). The corresponding figure for Norway spruce was 51% higher for E(3:28)D than for A(4:28). Irrespective of the large difference in thinning grade, the average annual production was identical for the A- and E-treatments (Table 8). The productivity of the A-treatment compared to the E-treatment was in the range 0.83-1.25 for Scots pine and 0.70-1.29 for Norway spruce and there was no correlation between relative production and relative thinning grade (Fig 9).

Thinning type

The thinning type did not have a statistically significant effect on total stem volume production for Scots pine or Norway spruce (Fig 10). However, there was a tendency towards reduced production as a result of thinning from above in Norway spruce; in addition, net stem volume production was significantly lower for thinning from above than thinning from below (Fig 10). Current annual stem volume increment was not affected by the thinning form for Scots pine (Table 9). For Norway spruce, there was no statistically significant difference in gross-CAI for the two thinning-type treatments; however, due to higher self thinning and a tendency towards lower gross-CAI, thinning from above (F(4:28)A) resulted in a significantly lower CAI excluding self thinning during the second and third periods than did thinning from below (A(4:28)) (Table 9).

Relative stem volume production

The relative stem volume production of thinned plots compared to unthinned ones at the same site was related to the mean basal area during the period between first thinning and the final measurement (Fig 11). For Scots pine, the relative production dropped sharply for average basal areas below 20-25 m^2 ha^{-1}, whereas it was fairly constant for larger average basal areas. For Norway spruce, average relative production increased with increasing average basal area but the variation associated with a specific basal area was large (Fig 11). The average relative production for all plots was higher for spruce than for pine but if relative production was compared at the same mean basal area, the difference was small. For average basal areas between 20 and 25 m^2 ha^{-1}, the relative production was 0.82 for both Scots pine and Norway spruce.

The relative production of thinned plots compared to unthinned ones at the same site exhibited a stronger correlation to relative basal area (the ratio between average basal area for thinned and untreated control plots) than mean basal area,

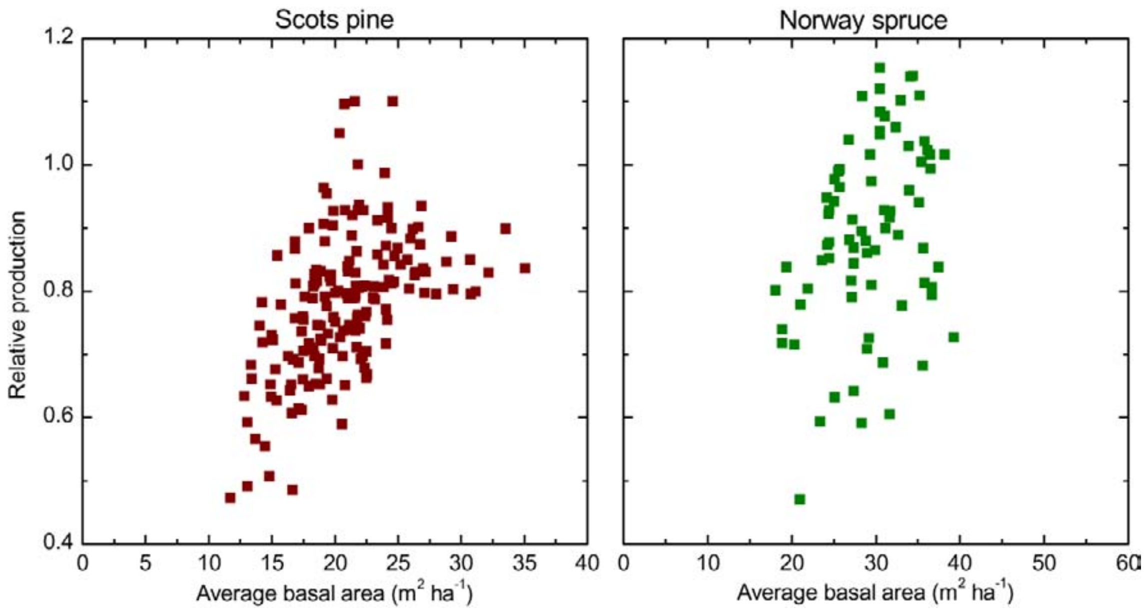

Figure 11. Relative production (production of thinned treatments in relation to the unthinned control at the same site) over the average basal area for the thinned plots of the Scots pine (left) and Norway spruce (right) experiments.

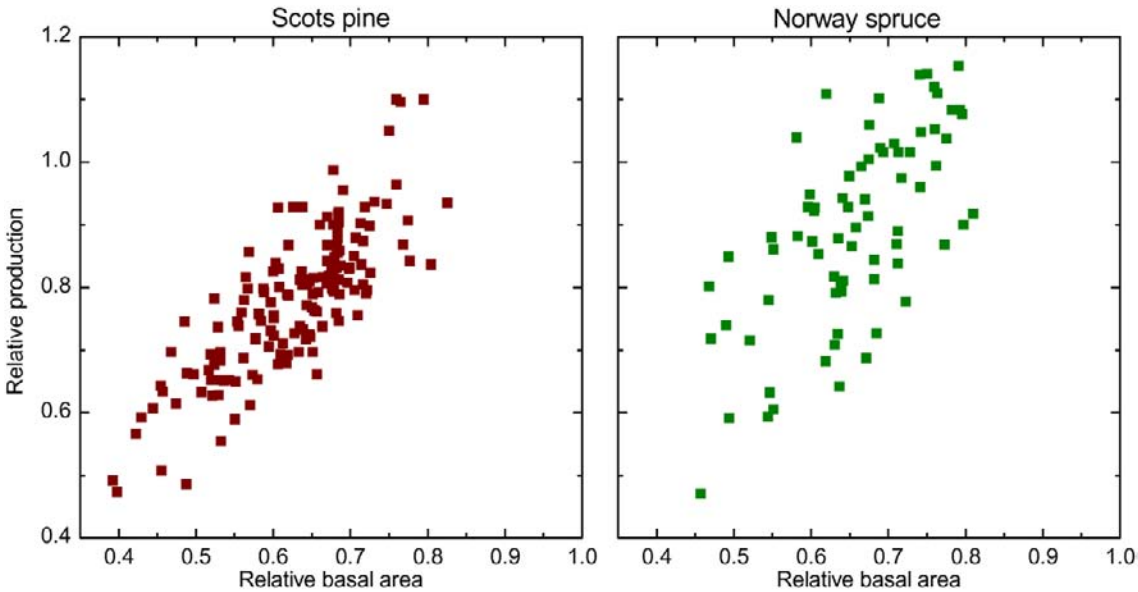

Figure 12. Relative production (production of thinned treatments in relation to the unthinned control at the same site) over relative basal area (average basal area of thinned plots for thinned treatments in relation to the unthinned control at the same site) for the thinned plots of the Scots pine (left) and Norway spruce (right) experiments.

especially for Scots pine (Fig 12). At the same relative basal area, the relative growth reduction was about 10% greater for Scots pine than for Norway spruce (Fig 12).

The stem density before the first thinning was not related to relative production for Scots pine whereas there was a weak positive correlation for Norway spruce (Fig 13).

Discussion

Thinning grade and interval between thinnings

The finding in this study that thinning decreased total production is in agreement with several previous studies (e.g. Møller, 1954; Braathe, 1957; Mäkinen & Isomäki, 2004a; 2004b). However, in some other studies, light and moderate thinnings have been found to increase gross stem volume production for Norway spruce (Holmsgaard, 1958; Pretzsch, 2004; Bergstedt & Jørgensen 1997). In this study, gross stem volume production in the Norway spruce light thinning treatment was not increased compared to the unthinned control, but it was the only thinning treatment which did not exhibit significantly lower production. However, for this species, it was only the extra heavy thinning treatments (C and D) that resulted in production losses of more than 10%. Wallentin (2007), arrived at a similar conclusion based on an analysis of 24 published Norway spruce thinning experiments. In order to affect absolute total production in Norway spruce significantly, the average basal area has to be reduced by more than 50-60%. In contrast to Norway spruce, thinning in Scots pine resulted in a substantial reduction in volume production. The relative production for thinned plots compared to the unthinned control plots varied between 65 and 80%. Judovalkis et al. (2005) concluded that, for stands aged 10-50 years, Norway spruce responded better to thinning than Scots pine. However, since the Norway spruce experiments were often established on sites with higher fertility compared to the Scots pine experiments, the comparison between the two species is confounded by differences in site fertility (Jonsson, 1995; Pettersson, 1996). Furthermore, as was the case in the current study, Scots pine is often thinned to a lower basal area after thinning than Norway spruce which affects production (see below).

In thinning guidelines and production models, the absolute basal area after thinning has often been used as an important independent variable to explain subsequent growth (Eriksson, 1976; Agestam, 1985; Ekö, 1985). In this study, the growth of thinned plots was correlated to average basal area during the whole study period and to the ratio of average basal area for thinned and unthinned plots. The correlation between average basal area and relative growth was

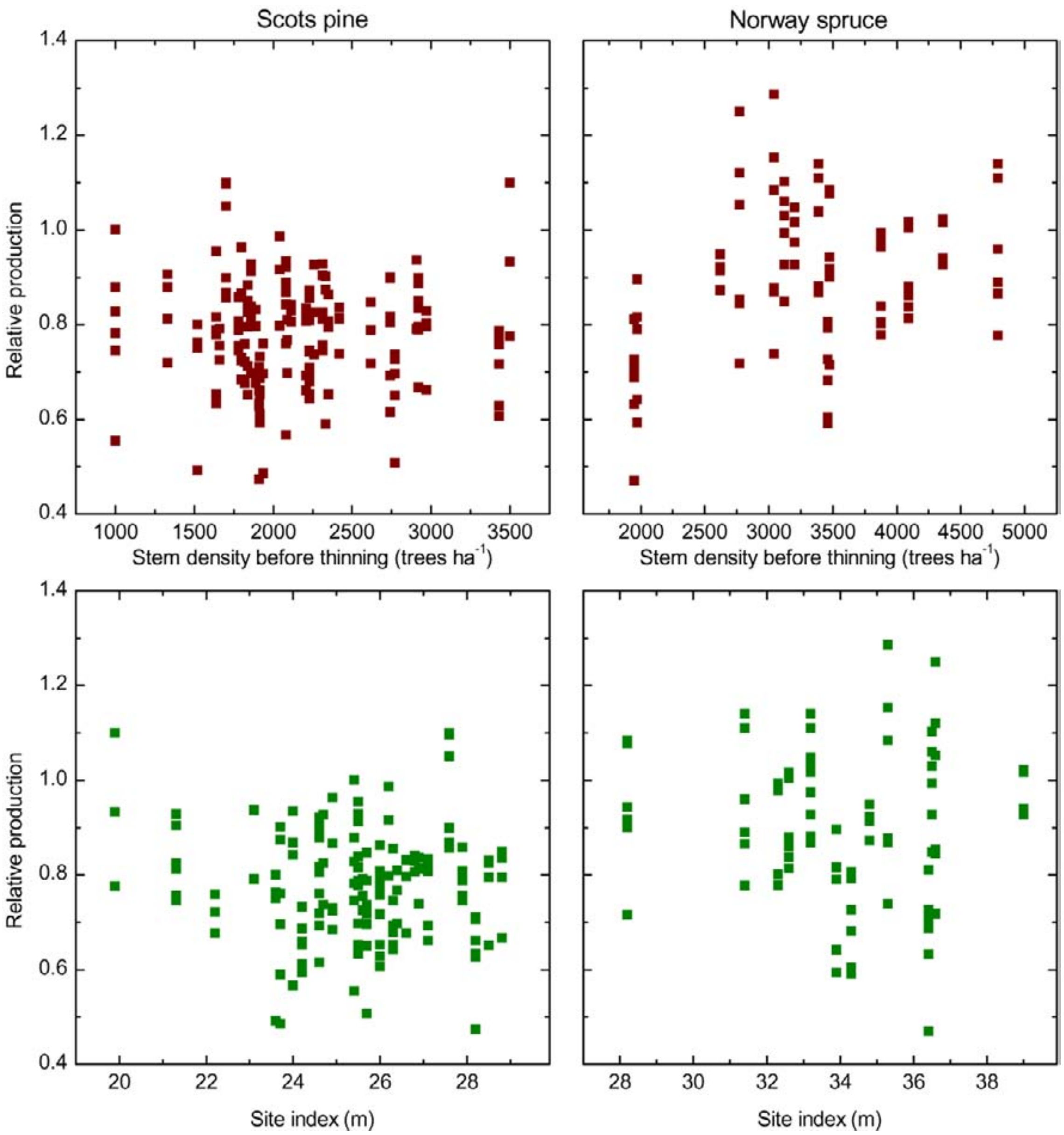

Figure 13. Relative production (production of thinned treatments in relation to the unthinned control at the same site) over tree density (stems ha^{-1}) before first thinning (top) and site index (m) (bottom) for the Scots pine and Norway spruce experiments.

relatively low, especially for Norway spruce. This is not surprising since variation in relative growth rate is not only dependent on the growth of thinned plots but also on the growth of the unthinned plots, and there should be very little correlation between average basal area of thinned plots and growth of unthinned plots. In contrast, relative growth was linearly correlated to relative basal area, and the correlation was stronger for Scots pine than for Norway spruce. One reason for the greater correlation between relative basal area and relative production for Scots pine than for Norway spruce was because thinning form and timing of first thinning affected the growth of Norway spruce but not of Scots pine. Therefore, in plots with the same relative basal area, different thinning forms or the timing of first thinning could partly explain the variation in the relative production of Norway spruce.

One way to interpret the correlation between relative basal area and relative production is to consider that a greater absolute basal area may be removed during the thinning of dense stands with a high basal area than when thinning stands with a low basal area; however, the basal area after thinning has to be higher in dense stands than less dense stands in order to avoid production losses compared to unthinned stands. Thus, it is not possible to give a conclusive recommendation for the amount of basal area that should remain after thinning in order to avoid production losses. However, it may be concluded that the basal area after thinning should be higher on fertile sites than on less fertile ones, higher for late thinnings than for the first thinning, and higher for Norway spruce than for Scots pine. These inferences are based on the empirical observations that the average basal area of unthinned stands is higher for fertile than for less fertile stands, higher in old stands than in younger stands and higher for Norway spruce than for Scots pine. In general, this is also in agreement with current thinning guidelines.

Responses by species

The growth of Scots pine was more sensitive to a reduction in relative basal area than Norway spruce. This result corresponds to the results obtained by Mäkinen & Isomäki (2004 a,b) who studied thinning in Norway spruce and Scots pine in Finland. The correlation between relative growth and relative basal area was approximately equivalent to that reported for Scots pine in other studies (Montero et al 2001, Mäkinen and Isomäki 2004 a). In contrast, the reduction in the growth of Norway spruce was greater in this study than has been reported in other studies (Wallentin, 2007). For example, Mäkinen & Isomäki (2004 b) found that a 40% reduction of the basal area relative to an unthinned control resulted in a decrease of less than 10% in terms of gross stem volume growth for Norway spruce. The results of this study indicated that for the same reduction of average basal area, volume production declined by approximately 20%. It can only be speculated why we found greater effects than that reported in previous studies. For example, the thinning treatments may have been more extreme than has normally been the case in the previous thinning experiments or the thinning from above and the single heavy thinning treatments may have yielded lower relative growth than would have been expected simply from the reduction in relative basal area.

Avoidance of density-dependent mortality

One of the aims with thinning is to remove trees before they are self-thinned (Wallentin, 2007; Agestam, 2009). The results of this study suggested that self thinning effects were largely eliminated via thinning. We found significantly higher self-thinning in the unthinned plots relative to thinned plots for both Scots pine and Norway spruce. The higher level of self-thinning resulted in higher net production for the A- and B-treatments than for the unthinned control in Norway spruce. This is in contrast to data reported by Mäkinen & Isomäki (2004 b), who found no effect of light and medium thinnings on net volume production compared to an untreated control. One important difference between the Mäkinen & Isomäki study and this one was the stem density before first thinning. In the former, the average stem density before thinning was about 2000 trees ha^{-1} compared to 3389 trees ha^{-1} in this study. Net-production for Scots pine was not significantly affected by the thinning treatments even though self-thinning was relatively high. The difference between Norway spruce and Scots pine with respect to net production of thinned plots in relation to the unthinned control in this study was, rather, dependent on the greater reduction in total production for thinned plots of Scots pine than for Norway spruce. This is in accordance with the results of Mäkinen & Isomäki (2004 a b), who found that both gross- and net production of Scots pine were significantly decreased by heavy thinning, whereas heavy thinning of Norway spruce, due to the small absolute effect on gross-production and greater self-thinning compared to control plots, did not affect net production. Another difference between the Norway spruce and Scots pine stands in the current study is that the Norway spruce stands were closer to their final felling age than the Scots pine stands. At the time of the final measurement, more than 20 years remained, on average, until final harvest for Scots pine, whilst the Norway spruce was on average less than 10 years away from final harvest. It is possible that self-thinning in unthinned Scots pine control plots between the time when the stands were measured for the last time and the final harvest will result in significantly higher net-production in the thinned plots. However, the current annual increment excluding self thinning at the time of the final measurement was not higher for thinned Scots pine plots than for the unthinned ones. If self-thinning is not drastically increased in the unthinned plots, it is therefore unlikely that net production will be significantly different between thinned and unthinned Scots pine plots at the time of final felling.

Gross- and net volume response patterns

Thinning experiments are often analysed in relation to total production (Eriksson & Karlsson, 1997; Mäkinen & Isomäki, 2004 a,b) but more relevant to practical forestry is the production of merchantable wood volume, so many thinning experiments have also been analysed in relation to this variable (Carbonnier, 1954; MacKenzie, 1962). Pretsch (2004) found that heavy thinning of Norway spruce and beech enhanced the production of merchantable timber as compared to very lightly thinned control plots, whilst extra heavy thinning of plots failed to increase the production of merchantable wood. In the current study, light thinning and heavy but less frequent thinning increased the production of merchantable wood compared to the untreated control for Norway spruce, whereas frequent, heavy thinning and a single extra heavy thinning resulted in the same level of production as the untreated control. For Scots pine, none of the thinning treatments enhanced the production of merchantable timber and it was significantly lower in the heavy thinning treatments C- and D than in the unthinned control. However, analysis of merchantable timber should be approached with caution since the concept of merchantable wood varies over time. There is a trend in Swedish forestry for harvesting more of the biomass than just stem-wood above a certain diameter (Egnell, 2009). With new harvesting equipment, it may be economical to harvest smaller trees and it is already economic, in some geographical regions, to harvest tops and branches for bioenergy (Egnell, 2009).

Effect of thinning on stem-volume growth

After the third thinning, the basal area was almost equal in the A- and C-treatments for Norway spruce but the annual growth was still significantly higher in the A-treatment during the subsequent growth period. This indicates that newly thinned stands have a higher growth rate than unthinned stands if they are compared at the same initial basal area. There are a number of possible explanations for this. First, the slash (tops and branches) that are retained after thinning may add fertility to the soil. It has been found that whole-tree harvest, where the slash is removed, results in decreased growth after thinning compared to normal stem-harvest (Jacobson et al. 2000; Egnell et al. 1998). Secondly, in the C-treatment the stems were chosen on just a single occasion at first thinning whereas the best stems were selected at the time of the three thinnings in the A-treatment. It is possible that this selection of vigorous trees and better spatial distribution of trees over the area may, to some extent, have contributed to the better growth in the thinned plots. Thirdly, trees in the C-treatment were larger, on average, than trees in the A-treatment and it has been proposed that production efficiency is lower for large trees than for smaller ones (Eide & Langsæter, 1941; Braathe, 1952; Mäkinen and Isomäki, 2004a).

Thinning effects on individual tree size

The average diameter of the final stand was increased by thinning for both Scots pine and Norway spruce. This result was similar to results presented in other studies of thinning in Scots pine and Norway spruce (Eriksson & Karlsson, 1997; Mäkinen & Isomäki, 2004 a,b). One major aim with thinnings is to increase diameter development and the average size of the trees at final harvest. The average size of the trees in the final stand is affected in two ways by thinning. First, diameter-growth of individual trees is increased by thinning. Second, the average diameter is increased because small trees are removed during thinning.

However, the average diameter of all trees, including trees actively removed during thinning and trees retained until the time of the final measurement, but excluding self-thinned trees, were significantly larger for the unthinned control than for all thinned plots in Scots pine and larger in unthinned control than in light thinning treatments in Norway spruce. The average diameter of all trees was low in the thinned plots because trees removed during thinning were the smallest ones. Another factor that contributed to the difference in total tree size was that self-thinning in control plots mainly affected the smallest trees and these were not included in the calculations. Because of the self-thinning of small trees, the difference in average diameter between thinned and unthinned plots was not as great as it would have been if all trees had survived. The net income from a tree is dependent on its size since both its value and the cost of harvesting are size-dependent; the larger average size of the trees in the unthinned plots will result in a higher net income per produced m^3 compared to that in the thinned plots.

This may, to some extent, counteract the disadvantage of late income in a net-present value analysis.

Delayed thinning treatments

Delaying first thinning did not affect total production. Mäkinen and Isomäki (2004 a & b) found no effect of the timing of commencing thinning of Norway spruce, but production of Scots pine was less affected by late thinnings than by early thinnings. The authors do however warn that the material in the late thinnings was weak and the difference may be partly due to random errors. To our knowledge, the current research is unique in comparing delayed thinning with normal thinning at the same site instead of comparing separate sites with different thinning commencement times. In this respect, the results of our experiment reflect the "true" effects of delaying the first thinning. Since total volume production was not affected by delaying first thinning, it may be economically profitable since larger trees and greater volume per area may be harvested during the thinning operations. However, there are aspects other than production associated with delayed thinning. It may be more difficult to remove large trees of poor quality in the thinning, since they have had more time to suppress their neighbours. Furthermore, the risk of wind-throw following thinning is increased in late first thinnings compared to earlier thinnings (Persson, 1975).

Thinning type

It has generally been believed that thinning from above reduces growth since there is negative selection during such thinnings because large trees that are growing well are harvested (Welander, 1910; Wahlgren, 1914; Jäghagen & Albrektson, 1989). However, small differences in site fertility in a stand or random damage affecting growth may result in differences in early growth between trees with similar genetic backgrounds. These initial differences in growth may be increased by asymmetric competition, leading to significant differences at the time of thinning (Nilsson, 1993). Thus, it is not certain that the largest trees in the forest have the best genetic growth potential. Furthermore, it has been shown that a retained cubic metre of trees in small diameter-classes exhibits higher stem volume production than a retained cubic-meter of large diameter classes (Eide & Langsæter, 1941; Braathe, 1952; Mäkinen & Isomäki, 2004a). This is probably because respiration losses in relation to stem volume production are greater for large trees than for small ones (Cannell, 1989). In the current study, thinning form (thinning from below compared to thinning from above) did not affect the growth of Scots pine whereas there was a tendency for reduced growth in the F-treatment for Norway spruce. There may be several reasons for the difference between the two tree species. First, thinning from above may have been a more extreme treatment in Norway spruce than in Scots pine stands since the diameter distribution is often wider for Norway spruce (Eriksson & Karlsson, 1997). However, the thinning ratio did not support this hypothesis. The thinning ratio was about equal, or slightly higher, for Scots pine, thus indicating that thinning from above removed large trees to a similar or greater extent in the Scots pine than the Norway spruce plots. Secondly, the negative selection may have been more pronounced in Scots pine than in Norway spruce. It has been shown that browsed Norway spruce trees, with better vitality than their neighbours at the time of browsing, will outgrow neighbouring trees over a 5-10 year period even if growth is reduced immediately after browsing (Bergquist et al. 2002). For Scots pine and for loblolly pine (*Pinus taeda*), it has been shown that the size of the seedling a couple of years after planting, i.e. before the onset of competition between trees, exhibits a good correlation with the tree's hierarchical position at the time of first thinning (Nilsson & Albrektson, 1994; Nilsson et al. 2002). Therefore, Norway spruce trees with good genetic growth capacity may be represented to a greater extent among the dominant trees, thus thinning from above may result in a greater negative selection effect on Norway spruce than Scots pine. In addition to this, the bulk of the Scots pine stands originated from natural regeneration or direct seeding whereas the majority of the Norway spruce stands were planted. It is possible that more uniform conditions during early establishment for the planted Norway spruce than for naturally regenerated or direct seeded Scots pine may have allowed early expression of genetic growth potential to a higher degree for Norway spruce than for Scots pine. Thirdly, the previously mentioned higher production efficiency of small trees compared to larger ones may be greater for Scots pine than for Norway spruce. Nilsson & Albrektsson (1993) showed that the growth efficiency of suppressed Scots pine trees was substantially better than for dominant ones.

Sources of variation and experimental approach

The effect of thinning on stem volume growth has been shown to vary between sites with different site conditions, e.g. availability of water (Skovsgaard, 2009). However, in the current study, there was no correlation between site index and reduced production for either Norway spruce or Scots pine. Thus, our study indicates that site condition variables that are included in the site index (e.g. availability of nutrients and water, length of the growing season and temperature during the growing season) do not interact with the negative effect of thinning on stem volume growth. In addition, we showed that stem density before first thinning had little effect on growth after thinning for Scots pine whereas there was a small positive effect for Norway spruce. However, the positive correlation for Norway spruce is mainly due to a single site with a low stem number before thinning. If this site is omitted, the stem number also had little effect on Norway spruce.

In order to avoid damage to soil and on the stems caused by harvesting equipment, the machinery was not allowed to operate inside the core plots in this experiment. In contrast, thinning operations during real forestry operations are dominated by mechanised harvesting systems, where the machines often use strip-roads for movement within the forest. The effect of strip-roads on production has been debated (Bucht, 1981; Niemistö, 1989) but this effect is not included in the current study. One possible effect of normal strip-roads after first thinning could be a 5-10% average reduction in growth over a 5-15 year-period (Eriksson et al. 1994). If strip-roads had been included in the experiment, production of thinned plots would have been reduced by about 3-7% but this reduction would probably not have led to different conclusions. The presence of strip-roads does not only result in reduced production because of increased thinning-grade but trees next to the strip-roads may be damaged by the harvesting machinery; this can take the form of either root-damage by the wheels or stem damage by the machines (Wallentin et al. 2007). Both types of damage lead to reduced growth and reduced timber-quality. Furthermore, it has been shown that strip-roads increase the risk of wind-throw (Persson, 1975). Neither of these effects was accounted for in the current study.

The experiment described herein differs from many other thinning experiments in that it has many replicates (especially for Scots pine) arranged in a well-planned statistical design. Furthermore, the initial research plan has not been changed over the course of the experiment. Another unique feature of this experiment is that the thinning treatments are more extreme than those usually applied in older thinning experiments (Wallentin, 2007). The many replicates and the distribution of experimental sites throughout Sweden gives high credibility to the conclusions and allows for generalisation about the effect of thinning on Scots pine. In contrast, the fewer Norway spruce replicates and the more restricted geographical distribution of experimental sites make the results less widely applicable. However, the experimental sites were chosen to represent even-aged, well stocked, pure or almost pure stands and hence they do not fully reflect the forest stands in Sweden. Normally, forest stands are more heterogeneous, with higher variability in stem number and tree species composition. This discrepancy between the experimental stands and normal forest stands should be kept in mind when generalizing the results obtained in this study.

Concluding notes

This study demonstrated that all thinning treatments decreased total gross stem volume production in Scots pine while only the heavy thinning treatments reduced stem volume production in Norway spruce. If production excluding self-thinning is compared, light thinning increased production for Norway spruce while there was no statistically significant difference between light thinning treatments and the unthinned controls in Scots pine. Therefore, this study indicates that forest management without thinning will result in a reduction in the merchantable timber volume from Norway spruce, whereas about the same merchantable volumes can be produced irrespective of thinning in Scots pine. The more negative correlation between thinning intensity and production in Scots pine than in Norway spruce was probably mostly a result of a lower basal area after thinning of the former. Delaying first thinning did not result in reduced production, for either Scots pine or Norway spruce, and there was no correlation between removed basal area and production if thinning was conducted to achieve the same basal area after thinning. However, the risk of wind-throw after late first thinning probably reduces the value of this method for increasing net income from first thinnings. Finally, thinning from above did not affect stem volume production for Scots pine, but there was a tendency towards decreased total stem volume production for Norway spruce. In addition, stem volume production excluding self-thinning was significantly lower following thinning from above than thinning from below for Norway spruce. Consequently, it could be economically advantageous to use thinning from above at least in early thinnings in order to increase the dimension of the trees removed; however, thinning from above reduces the dimension of trees remaining until final felling and this will have a negative effect on the economic value at final harvest. The total value, including both an increase in the value of timber removed at thinning and the decrease in value at final felling, must be analysed before thinning from above can be recommended.

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Appendix

Appendix 1. Description of Scots pine sites

Included [a]	Site no.	Lat	Long	Reg. met. [b]	H_{100} [c]	Estab. of plots	At establishment: Tree species comp. [d]	At establishment: Basal area (m^2 ha^{-1})	At establishment: No. of stems ha^{-1}	At establishment: H_{dom} [e] (m)	At establishment: Age (years)	At 2:nd thinning: H_{dom} (m)	At 2:nd thinning: Age (years)	At 3:d thinning: H_{dom} (m)	At 3:d thinning: Age (years)	At 4:th thinning: H_{dom} (m)	At 4:th thinning: Age (years)	At last neasuremen: H_{dom} (m)	At last neasuremen: Age (years)	Thinning treatments: A(3:18)	B(2:15)	C(1:10)	D(3:13)	E(2:18)D	F(3:18)A	I(0:0)
x	787	60°47'	17°12'	DS	28.4	1973	100:0:0	37.0	3741	14.6	33	18.1	41	20.2	48	23.1	57	24.7	65	x	x	x	x		x	x
x	895	60°17'	14°58'	NR	25.4	1977	100:0:0	24.7	2050	15.0	42	18.2	52	20.3	64			21.9	70	x	x	x	x	x	x	x
x	900	58°21'	14°18'	DS	27.0	1966	96:3:1	26.4	1804	14.5	36	17.0	44	20.4	57	22.8	69	24.4	77	x	x	x	x	x	x	x
x	902	60°00'	15°18'	DS	25.4	1969	98:2:0	18.9	1671	13.8	37	16.0	46	19.4	56			21.8	75	x	x	x	x	x	x	x
x	910	57°20'	14°05'	DS	25.7	1966	99:1:0	18.6	1559	13.9	37	17.2	48	19.6	59			22.6	77	x	x	x	x		x	x
x	912	57°15'	15°32'	DS	22.8	1969	99:1:0	17.8	1968	12.6	40	15.4	52	18.2	66	19.8	76			x	x	x	x	x	x	x
x	913	57°38'	15°18'	DS	21.0	1972	99:1:0	19.6	1936	13.1	48	16.5	62	18.5	76			19.8	82	x	x	x	x	x	x	x
x	918	60°38'	15°34'	DS	22.9	1970	100:0:0	25.1	2941	14.7	48	17.6	61	19.8	78			21.2	84	x	x	x	x	x	x	x
x	922	57°53'	15°01'	DS	23.6	1967	89:11:0	23.4	2314	15.2	46	17.2	54	20.6	70	23.2	86			x	x	x	x	x	x	x
x	923	57°50'	13°52'	DS	23.4	1973	96:4:0	25.2	3477	13.5	41	16.8	53	19.4	65			21.6	75	x	x	x	x	x	x	x
x	924	56°57'	14°03'	PI	25.7	1968	100:0:0	21.1	1689	12.9	34	16.0	42	19.1	50	21.9	59	23.9	70	x	x	x	x	x	x	x
x	926	64°23'	18°35'	DS	22.9	1969	99:0:1	22.6	1452	15.0	49	17.6	62	19.2	76			21.0	85	x		x		x	x	x
x	927	65°09'	19°06'	NR	23.4	1969	96:2:2	27.9	2502	14.3	45	17.5	58	19.2	69			20.8	83	x		x		x	x	x
x	929	59°10'	14°23'	NR	25.1	1970	95:5:0	24.3	2011	15.4	45	18.2	57	21.3	72			23.0	80	x	x	x	x	x	x	x
x	930	60°00'	15°18'	DS	25.9	1966	97:3:0	20.6	2070	12.4	32	14.7	39	17.7	48	20.7	59	22.2	73	x	x	x	x	x	x	x
x	931	57°33'	14°14'	DS	25.4	1973	94:3:3	20.0	1969	14.1	38	16.7	47	20.1	60			22.6	71	x	x	x	x	x	x	x
x	934	61°32'	15°58'	DS	26.3	1971	95:4:2	22.8	2440	13.8	35	16.4	43	19.7	56			20.6	66	x		x		x	x	x
x	936	61°52'	16°20'	DS	25.2	1974	100:0:0	20.9	2043	13.2	36	16.2	47	18.4	60			20.0	69	x		x			x	x
x	939	62°45'	15°14'	DS	23.8	1981	99:1:0	27.6	2406	12.3	36	16.1	46	17.9	52			20.9	61	x		x		x	x	x
x	940	56°23'	14°16'	DS	23.0	1969	95:4:1	20.2	1284	14.8	47	17.7	61	20.7	75			22.5	85	x	x	x	x	x	x	x
x	945	63°28'	16°13'	PI	26.2	1985	100:0:0	35.1	3091	13.2	34	16.3	42	19.1	50			21.3	56	x		x		x	x	x
x	946	64°30'	18°46'	DS	24.5	1976	92:0:8	24.0	2448	12.2	34	15.3	43	17.4	51			20.5	65	x		x			x	x
x	947	64°30'	18°46'	DS	24.3	1978	95:0:5	25.0	2298	12.7	36	16.0	45	17.5	54			20.1	64	x		x			x	x
x	948	63°45'	18°30'	PI	24.4	1976	95:0:5	27.1	2142	12.8	36	15.6	44	17.4	51			21.9	66	x		x			x	x
x	952	66°43'	22°38'	NR	22.4	1975	99:1:0	23.1	1613	15.7	54	18.4	71	19.3	80			20.2	86	x		x			x	x
x	989	62°37'	13°18'	DS	21.8	1972	96:2:2	31.1	2225	14.9	52	18.1	64	20.7	77			21.6	86	x		x			x	x
x	990	62°38'	13°18'	DS	19.1	1972	93:7:0	30.1	3048	12.7	52	16.1	66	17.8	77			19.2	86	x		x			x	x
x	991	64°21'	19°49'	DS	22.5	1976	100:0:0	24.9	2808	12.6	40	15.4	49	17.2	60			19.8	70	x		x			x	x
x	996	62°23'	15°08'	NR	26.9	1981	100:0:0	28.3	1830	14.2	36	16.8	43	19.2	52			22.1	62	x		x		x	x	x
x	999	63°08'	16°22'	DS	24.3	1976	90:10:0	22.3	1918	12.2	35	15.1	44	18.4	53			21.2	63	x		x			x	x
x	1000	65°50'	20°52'	PI	24.7	1981	100:0:0	26.3	2360	12.6	36	15.8	47	17.8	55			19.8	62	x		x			x	x
x	1004	63°21'	14°14'	DS	22.5	1975	96:4:0	24.0	1857	13.9	46	17.1	58	18.7	69			20.3	77	x		x			x	x
x	1005	63°49'	16°18'	NR	25.3	1980	100:0:0	27.6	1958	13.4	37	15.8	44	18.8	53			21.7	64	x		x			x	x
x	1007	63°37'	17°26'	DS	23.2	1977	99:1:0	20.3	1663	12.7	39	15.8	49	18.3	59			21.0	68	x		x			x	x
x	1009	63°37'	17°51'	DS	22.9	1981	100:0:0	19.0	1418	11.9	37	15.2	47	17.1	55			19.5	63	x		x		x	x	x
	679	60°07'	13°26'	NR	29.3	1970	100:0:0	32.6	4053	11.9	26	14.1	32	17.8	40	20.9	48	26.6	64	x	x	x		x	x	x
	911	58°36'	15°16'	DS	24.1	1967	96:1:3	28.0	2766	15.1	45	16.8	53	20.2	66					x	x	x	x	x	x	x
	933	59°07'	15°47'	NR	21.7	1973	99:1:0	16.2	1490	13.7	48	16.9	65	19.0	78					x	x	x	x	x	x	x
	935	61°55'	15°42'	DS	24.4	1978	100:0:0	24.4	1518	15.0	44	18.6	58	20.9	73					x		x			x	x
	938	64°04'	17°24'	NR	17.9	1974	99:1:0	14.6	1872	12.1	58	15.1	75	17.4	89					x		x		x	x	x
	951	66°56'	23°48'	NR	21.1	1975	100:0:0	26.6	2140	13.4	49	15.8	61	18.0	79					x		x			x	x
	987	60°46'	17°17'	DS	24.3	1970	95:4:1	30.4	1797	14.7	43	18.1	54	20.2	64			21.8	73				x		x	x
	992	65°53'	20°48'	DS	21.0	1980	98:0:2	18.5	1545	12.8	46	15.8	58	18.0	70					x		x			x	x
	993	66°39'	19°56'	NR	17.7	1983	100:0:0	16.9	1603	11.2	52	14.0	66					15.8	75	x		x			x	x
	994	67°28'	23°06'	NR	19.4	1978	100:0:0	21.7	1858	12.2	51	15.1	67	16.9	79					x		x		x	x	x
	997	64°21'	15°39'	PI	24.8	1984	100:0:0	34.4	2531	14.8	42									x		x		x	x	x
	1006	66°23'	20°32'	PI	22.9	1986	100:0:0	26.6	2276	11.8	37	14.6	47	17.8	56					x		x			x	x
	1008	66°11'	21°04'	PI	23.3	1986	99:0:1	25.6	1862	12.5	38	15.2	49	18.1	58					x		x			x	x
Average					23.7			24.4	2152.4	13.5	41.4	16.4	52.3	18.9	63.2	21.8	64.9	21.4	72.2							
Standard deviation					2.387			4.98848	604.6	1.16	6.88	1.2	9.473	1.2	11.27	1.34	12.97	1.84	8.606							

[a] X if the site is included in this study. Only sites which had undergone three thinnings and had at least one measurement period after the third thinning were included for Scots pine.

[b] Regeneration method PI=planting; NR=natural regeneration; DS=Direct seeding

[c] H_{100} Site index, dominant height at age 100 years, calculated at the last measurement

[d] Per cent of total basal area of Scots pine:Norway spruce:Broadleaves

[e] Top height based on 100 largest trees ha^{-1}

Appendix 2. Description of Norway spruce sites

							At establishment					At 2:nd thinning		At 3:d thinning		At 4:th thinning		At 5:th thinning		At 6:th thinning		At last neasuremen		Thinning treatments						
Included [a]	Site no.	Lat	Long	Reg. met.[b]	H_{100}[c]	Estab. of plots	Tree species comp.[d]	Basal area (m^2 ha^{-1})	No. of stems ha^{-1}	H_{dom}[e] (m)	Age (years)	H_{dom} (m)	Age (years)	H_{dom} (m)	Age (years)	H_{dom} (m)	Age (years)	H_{dom} (m)	Age (years)	H_{dom} (m)	Age (years)	H_{dom} (m)	Age (years)	A(3:18)	B(2:15)	C(1:10)	D(3:13)	E(2:18)D	F(3:18)A	I(0:0)
x	682	59°29'	14°13'	Pl	30.82	1973	0:100:0	28.3	4116	12.8	30	16	37	20	44	21.9	52					26.1	64	x	x	x	x			x
x	905	59°07'	14°29'	Pl	32.42	1968	0:100:0	34.5429	1816	20.4	44.7	22	49.71	24	57.71	27.2	68.71					31.6	83.71	x	x	x	x	x	x	x
x	907	59°14'	12°02'	NR	34.94	1971	6:93:1	24.98	3110	13.8	27	17	35	21	41	22.4	46					28.2	63	x	x	x		x		x
x	914	57°32'	15°36'	Pl	32.26	1975	0:100:0	28.6833	1799	13.2	29	16	34	20	42	22.1	48	24.5	57					x	x	x		x	x	x
x	915	56°45'	14°08'	Pl	33.56	1968	0:100:0	30.86	2902	14.1	29	18	36	20	42	22.9	47	26.1	55	27.5	61			x	x	x		x		x
x	919	58°17'	15°36'	Pl	36.54	1980	0:100:0	38.38	4452	13.5	25	17	30	20	35	21.8	39	26.3	47					x	x	x		x		x
x	920	56°43'	13°49'	Pl	31.48	1967	0:100:0	39.8429	3247	16.3	37	20	44	22	52	26.2	64	27.6	71					x	x	x	x	x	x	x
x	921	56°21'	13°04'	Pl	34.28	1966	0:99:1	39.6857	3977	15	30.1	17	35.14	20	42.14	22.8	49.14	25	56.14	26.7	64.14	28.3	71.14	x	x	x	x	x	x	x
x	928	58°52'	14°41'	Pl	38.14	1980	0:100:0	30.375	2629	13	23	17	29	20	37	23.1	43					26.7	51	x	x	x	x	x	x	x
x	941	56°05'	13°13'	Pl	30.45	1968	0:100:0	34.8571	4966	12.9	31	16	36	18	43	21.2	49	24.5	58			26	64	x	x	x	x	x	x	x
x	943	56°10'	13°34'	Pl	28.33	1969	0:100:0	33.9143	4173	14	37	16	44	20	55	21.7	66					23.5	72	x	x	x	x	x	x	x
x	944	56°12'	13°14'	Pl	32.83	1971	0:100:0	36	3654	14.6	31	18	38	21	44	23	50	24.5	57	28.3	66			x	x	x	x	x	x	x
x	949	58°49'	16°56'	Pl	33.15	1973	0:100:0	35.3714	3213	13.4	28	16	33	20	39	22.4	44					25	51	x	x	x	x	x	x	x
	785	56°54'	12°40'	Pl	37.45	1971	0:100:0	46.1	4311	15.5	28	19	33	22	38												x		x	x
	901	58°11'	13°27'	Pl	31.68	1979	0:100:0	23.7857	1347	12.9	29	16	35	18	40							24	53.43	x	x	x	x	x	x	x
	916	56°57'	14°36'	Pl	34.35	1969	0:100:0	28.1667	3083	13.2	27.3	17	35	20	40	21.6	44	24.8	52	26.7	58						x		x	x
	917	56°28'	13°54'	Pl	28.3	1972	4:96:0	25.7	4243	12.6	34	14	42	18	52	19.9	62	21.2	68								x		x	x
	925	56°52'	13°37'	Pl	31.27	1973	2:98:0	27.2429	2645	15.6	36	17	43	20	51	21.8	62							x	x	x	x	x	x	x
	932	59°38'	16°57'	Pl	31.4	1968	0:100:0	29.9667	3063	15.3	35	17	42	19	49	22.4	60					26.1	74				x		x	x
	937	61°41'	17°18'	Pl	32.33	1974	0:100:0	38.1667	2166	12.8	28	16	34	20	39							30.3	61	x		x				x
	942	56°27'	14°24'	Pl	32.94	1967	0:100:0	35.4333	4293	15.4	33	18	38	20	45	22.9	55							x	x	x	x		x	x
	950	63°14'	18°44'	Pl	35.58	1975	0:100:0	35.8	2478	14.2	27	16	33	18	38							26.6	59	x		x				x
	995	60°33'	17°25'	Pl	31.88	1979	0:99:1	32.56	2140	13.5	30	18	37	20	42							25.4	55.4	x	x	x		x		x
Average					32.9			33.0	3209.7	14.3	30.8	17.1	37.1	20.1	43.8	22.6	52.7	24.9	57.9	27.3	62.3	26.8	63.3							
Standard deviation					2.523			5.53676	990.7	1.72	4.77	1.6	4.972	1.3	6.108	1.69	8.942	1.77	7.419	0.78	3.524	2.33	9.814							

[a] X if the site is included in this study. For Norway spruce, only sites with four thinnings and at least one measurement period after the fourth thinning were included.

[b] Regeneration method Pl=planting; NR=natural regeneration

[c] H_{100} Site index, dominant height at age 100 years, calculated at the last measurement

[d] Per cent of total basal area of Scots pine:Norway spruce:Broadleaves

[e] Top height based on 100 largest trees ha^{-1}

Appendix 3. Results of the analysis of variance in total stem volume growth from first thinning to last measurement. Effects of thinning grade, interval between thinning, delayed first thinning and thinning type (c.f. Figure 6, 8 and 10)

A. Scots pine

Parameters	35 sites comparing A(3:18), C(1:10), I(0:0)				15 sites comparing A(3:18) (2:15), C(1:10), D(3:13), I(0:(				20 sites comparing A(3:18), E(2:18)D, I(0:0)				35 sites comparing A(3:18), F(3:18)A, I(0:0)			
	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value
Production including self thinning																
Site	34	4778	13.16	<0.0001	14	7975	21.23	<0.0001	19	2904	8.62	<0.0001	34	4973	17.16	<0.0001
Treatment	2	54740	150.75	<0.0001	4	20103	53.51	<0.0001	2	16708	49.56	<0.0001	2	26269	90.64	<0.0001
Model	36	7554	20.8	<0.0001	18	10670	27.1	<0.0001	21	4219	12.51	<0.0001	36	6156	21.24	<0.0001
MSE	68	363			74	393			38	337			68	289		
Production excluding self thinning																
Site	34	5359	4.61	<0.0001	14	5337	9.6	<0.0001	19	3585	4.75	<0.0001	34	4557	5.58	<0.0001
Treatment	2	18040	15.52	<0.0001	4	5258	9.44	<0.0001	2	910	1.21	0.3106	2	2441	3.52	0.035
Model	36	6064	5.22	<0.0001	18	5319	9.55	<0.0001	21	3330	4.41	<0.0001	36	4439	6.41	<0.0001
MSE	68	1162			74	556			38	755			68	693		

B. Norway spruce

Parameters	13 sites comparing (4:28), B(2:23); C(1:12), I(0:(				9 sites comparing A(4:28) (2:23), C(1:12), D(4:20), I(0:(				12 sites comparing A(4:28), E(3:28)D, I(0:0)				9 sites comparing A(4:28), F(4:28)A, I(0:0)			
	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value
Production including self thinning																
Site	12	15682	5.67	<0.0001	8	12853	3.36	0.0066	11	14159	4.94	0.0007	8	15705	5.71	0.0015
Treatment	3	20543	7.43	0.0005	4	20388	5.33	0.0021	2	5240	1.83	0.184	2	11585	4.21	0.0339
Model	15	16654	6.02	<0.0001	12	15365	4.02	0.0008	13	12787	4.47	0.001	10	14881	5.41	0.0015
MSE	36	2766			32	3823			22	2863			16	2748		
Production excluding self thinning																
Site	12	29878	8.56	<0.0001	8	20717	5.75	0.0001	11	15767	4.14	0.0022	8	20576	8.14	0.0002
Treatment	3	14694	4.21	0.0119	4	11765	3.27	0.0236	2	12957	3.4	0.0517	2	14635	5.79	0.0128
Model	15	26841	7.69	<0.0001	12	17733	4.92	0.0001	13	15335	4.02	0.002	10	19388	7.67	0.0002
MSE	36	3490			32	3603			22	3810			16	2528		

Appendix 4. Results of the analysis of variance for stem volume of trees with diameter at breast height (DBH) larger than 8 cm at the time of thinning or at last measurement. Effects of thinning grade and interval between thinning (c.f. Figure 7)

	Scots pine				Norway spruce			
	15 sites comparing A(3:18) B(2:15), C(1:10), D(3:13), I(0:0)				9 sites comparing A(4:28) B(2:23), C(1:12), D(4:20), I(0:0)			
	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value
Site	14	21462	26.38	<0.0001	8	38671	7.14	<0.0001
Treatment	4	5350	6.58	0.0002	4	14578	2.69	0.0486
Model	18	17882	21.98	<0.0001	12	30640	5.66	<0.0001
MSE	74	813			32	5418			

Appendix 5. Results of the analysis of variance for current annual increment (CAI, m^3 ha^{-1} $year^{-1}$). Scots pine - Effects of thinning grade and interval between thinning (c.f. Table 6)

Scots pine (35 sites comparing A3:18), C(1:10) and I(0:0))

Parameters	1:st-2:nd thinning				2:nd-3:rd thinning				3:rd-last measurement			
	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value
Production including self thinning												
Site	34	12.55	18.26	<0.0001	34	472.7	16.8	<0.0001	34	17.65	13.24	<0.0001
Treatment	2	93.15	135.31	<0.0001	2	92.26	46.13	55.75	2	52.85	36.65	<0.0001
Model	36	17.03	24.76	<0.0001	36	15.69	18.97	<0.0001	36	19.61	14.7	<0.0001
MSE	68	0.688			68	0.827			68	1.33		
Production excluding self thinning												
Site	34	11.47	14.89	<0.0001	34	15.02	8.15	<0.0001	34	38.87	4.11	<0.0001
Treatment	2	81.31	105.49	<0.0001	2	8.91	4.83	0.0109	2	3.35	0.35	0.7027
Model	36	15.35	19.92	<0.0001	36	14.68	7.96	<0.0001	36	36.91	3.9	<0.0001
MSE	68	0.771			68	1.84			68	9.46		

Scots pine (15 sites comparing A(3:18), B(2:15, C(1:10), D(3:13) and I(0:0))

Parameters	1:st-2:nd thinning				2:nd-3:rd thinning				3:rd-last measurement			
	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value
Production including self thinning												
Site	14	26.1	52.76	<0.0001	14	20.28	28.4	<0.0001	14	33.94	32.76	<0.0001
Treatment	4	14.18	28.65	<0.0001	4	17.94	25.11	<0.0001	4	32.86	31.71	<0.0001
Model	18	23.45	47.4	<0.0001	18	19.76	27.67	<0.0001	18	33.71	32.53	<0.0001
MSE	56	0.495			56	0.714			56	1.03		
Production excluding self thinning												
Site	14	24.18	43.85	<0.0001	14	13.11	13.31	<0.0001	14	25.34	12.27	<0.0001
Treatment	4	10.36	18.81	<0.0001	4	7.87	7.96	<0.0001	4	7.66	3.71	0.0095
Model	18	21.11	38.79	<0.0001	18	11.95	12.12	<0.0001	18	21.41	10.37	<0.0001
MSE	56	0.551			56	0.986			56	2.065		

Appendix 6. Results of the analysis of variance for current annual increment (CAI, $m^3\ ha^{-1}\ year^{-1}$). Norway spruce - Effects of thinning grade and interval between thinning (c.f. Table 6)

Norway spruce (35 sites comparing A(4:28), C(1:12) and I(0:0))

Parameters	1:st-2:nd thinning				2:nd-3:rd thinning				3:rd-4:th thinning				4:th-last measurement			
	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value
Production including self thinning																
Site	8	80.32	23.17	<0.0001	8	101.9	32.05	<0.0001	8	98.93	25.51	<0.0001	8	99.01	18.58	<0.0001
Treatment	4	61.48	17.73	<0.0001	4	19.07	6.01	0.002	4	19.67	5.07	0.0049	4	8.32	1.62	0.202
Model	12	76.55	22.08	<0.0001	12	85.36	26.84	<0.0001	12	83.08	21.43	<0.0001	12	80.93	15.19	<0.0001
MSE	32	3.47			32	3.18			32	3.88			32	5.32		
Production excluding self thinning																
Site	8	123.38	25.06	<0.0001	8	95.12	14.54	<0.0001	8	121.23	19.14	<0.0001	8	38.87	4.11	<0.0001
Treatment	4	70.46	14.31	<0.0001	4	23.92	3.66	0.0212	4	17.14	2.71	0.0596	4	3.35	0.35	0.7027
Model	12	112.79	22.91	<0.0001	12	80.88	12.36	<0.0001	12	100.4	15.86	<0.0001	12	36.91	3.9	<0.0001
MSE	32	4.92			32	6.54			32	6.33			32	9.46		

Norway spruce (9 sites comparing A(4:28), B(2:23), C(1:12), D(4:20) and I(0:0))

Parameters	1:st-2:nd thinning				2:nd-3:rd thinning				3:rd-4:th thinning				4:th-last measurement			
	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value
Production including self thinning																
Site	12	99.05	23.91	<0.0001	12	139.51	34.02	<0.0001	12	118.08	22.97	<0.0001	12	60.04	12	<0.0001
Treatment	3	26.69	6.44	0.0006	3	16.06	3.52	0.0106	3	20.17	3.92	0.0106	3	30.38	6.07	0.0009
Model	15	74.92	18.09	<0.0001	15	98.36	23.99	<0.0001	15	85.44	16.62	<0.0001	15	50.15	10.02	<0.0001
MSE	36	4.14			36	4.1			36	5.14			36	5.01		
Production excluding self thinning																
Site	12	181.1	30.57	<0.0001	12	127.95	16.97	<0.0001	12	119.98	17.8	<0.0001	12	67.26	8.33	<0.0001
Treatment	3	28.18	4.76	0.004	3	17.15	2.27	0.083	3	18.97	2.81	0.0415	3	22.63	2.91	0.0367
Model	15	130.09	21.97	<0.0001	15	91.02	12.07	<0.0001	15	86.31	12.81	<0.0001	15	52.39	6.74	<0.0001
MSE	36	5.92			36	7.54			36	6.73			36	7.76		

Appendix 7. Results of the analysis of variance for current annual increment (CAI, m^3 ha^{-1} $year^{-1}$). Scots pine - Effects of delayed first thinning and thinning type (c.f. Table 8 and 10)

Scots pine (20 sites comparing A(3:18), E(2:18)D and I(0:0))

Parameters	1:st-2:nd thinning				2:nd-3:rd thinning				3:rd-last measurement			
	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value
Production including self thinning												
Site	19	12.85	20.08	<0.0001	19	12.47	15.86	<0.0001	19	13.27	10.9	<0.0001
Treatment	2	3.31	5.18	0.0102	2	16.94	16.94	<0.0001	2	38.11	31.3	<0.0001
Model	21	11.94	18.66	<0.0001	21	12.91	16.4	<0.0001	21	15.63	12.84	<0.0001
MSE	38	0.64			38	0.7786			38	1.21		
Production excluding self thinning												
Site	19	12.03	15.25	<0.0001	19	14.4	13.86	<0.0001	19	37.25	8.52	<0.0001
Treatment	2	1.94	2.46	0.0989	2	5.45	5.24	0.0098	2	0.605	0.14	0.8711
Model	21	11.07	14.03	<0.0001	21	13.57	13.04	<0.0001	21	33.75	7.72	<0.0001
MSE	38	0.788			38	1.04			38	4.37		

Scots pine (35 sites comparing A(3:18), F(3:18)A and I(0:0))

Parameters	1:st-2:nd thinning				2:nd-3:rd thinning				3:rd-last measurement			
	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value
Production including self thinning												
Site	34	15.61	42.41	<0.0001	34	13.77	16.23	<0.0001	34	17.22	16.98	<0.0001
Treatment	2	8.12	22.09	<0.0001	2	30.49	35.94	<0.0001	2	47.34	46.68	<0.0001
Model	36	15.19	41.28	<0.0001	36	14.69	17.33	<0.0001	36	18.89	18.63	<0.0001
MSE	68	0.37			68	0.848			68	1.01		
Production excluding self thinning												
Site	34	14.32	26.7	<0.0001	34	17.02	10.62	<0.0001	34	28.06	6.77	<0.0001
Treatment	2	7.5	13.98	<0.0001	2	9.79	6.1	0.0036	2	0.705	0.17	0.844
Model	36	13.94	25.99	<0.0001	36	16.62	10.37	<0.0001	36	26.53	6.4	<0.0001
MSE	68	0.536			68	1.61			68	4.15		

Appendix 8. Results of the analysis of variance for current annual increment (CAI, m^3 ha^{-1} $year^{-1}$). Norway spruce - Effects of delayed first thinning and thinning type (c.f. Table 8 and 10)

Norway spruce (12 sites comparing A(4:28), e(3:28)d and I(0:0))

Parameters	1:st-2:nd thinning				2:nd-3:rd thinning				3:rd-4:th thinning				4:th-last measurement			
	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value
Production including self thinning																
Site	11	76.94	20.66	<0.0001	11	89.27	17.54	<0.0001	11	66.25	20.77	<0.0001	11	73.76	16.39	<0.0001
Treatment	2	0.32	0.09	0.9179	2	1.07	0.21	0.8115	2	2.66	0.84	0.447	2	16.03	3.56	0.0457
Model	13	65.15	17.49	<0.0001	13	75.7	14.88	<0.0001	13	56.46	17.7	<0.0001	13	64.87	14.52	<0.0001
MSE	22	3.72			22	5.09			22	3.18			22	4.5		
Production excluding self thinning																
Site	11	94.72	18.55	<0.0001	11	78.27	10.99	<0.0001	11	71.61	12.69	<0.0001	11	100.9	9.95	<0.0001
Treatment	2	3.76	0.74	0.4898	2	24.05	3.38	0.0525	2	27.21	4.82	0.018	2	27.19	2.68	0.0908
Model	13	80.73	15.81	<0.0001	13	69.92	9.82	<0.0001	13	64.77	11.48	<0.0001	13	89.6	8.83	<0.0001
MSE	22	5.1			22	7.11			22	5.64			22	10.15		

Norway spruce (9 sites comparing A(4:28), F(4:28)A and I(0:0))

Parameters	1:st-2:nd thinning				2:nd-3:rd thinning				3:rd-4:th thinning				4:th-last measurement			
	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value	df	Mean square	F-value	p-value
Production including self thinning																
Site	8	65.02	19.96	<0.0001	8	94.86	22.87	<0.0001	8	69.99	20.47	<0.0001	8	35.27	5.68	0.0016
Treatment	2	2.76	0.85	0.4465	2	10.35	2.49	0.114	2	8.73	2.55	0.109	2	22.47	3.62	0.0504
Model	10	52.58	16.14	<0.0001	10	77.96	18.8	<0.0001	10	57.74	16.88	<0.0001	10	32.71	5.27	0.0017
MSE	16	3.26			16	4.15			16	3.42			16	6.21		
Production excluding self thinning																
Site	8	94.02	20.4	<0.0001	8	84.67	15.13	<0.0001	8	80.63	14.99	<0.0001	8	74.98	7.83	0.0003
Treatment	2	2.04	0.44	0.6495	2	28.18	5.04	0.0201	2	30.21	5.62	0.0142	2	25.41	2.65	0.1013
Model	10	75.62	16.41	<0.0001	10	73.37	13.11	<0.0001	10	70.54	13.12	<0.0001	10	65.07	6.79	0.0004
MSE	16	4.61			16	5.59			16	5.38			16	9.58		

Photo appendix

Photos were taken in two stands (Site 905 in Norway spruce and site 929 in Scots pine) before and after thinning and in 2004 after four thinnings in Norway spruce and three thinnings in Scots pine.

Site 905, treatment I(0:0) 1973.

Site 905, treatment I(0:0) 1973.

Site 905, Treatment A(4:28). Before thinning 1968.

Site 905, Treatment A(4:28). After thinning 1968.

Site 905, Treatment A(4:28). After four thinnings, 2004.

Site 905, Treatment B(2:23). Before thinning, 1968.

Site 905, Treatment B(2:23). Before thinning, 1968.

Site 905, Treatment B(2:28). After two thinnings, 2004.

Site 905, Treatment C(1:12). After first thinning, 1968.

Site 905, Treatment C(1:12). After one thinning, 2004.

Site 905, Treatment D(4:20). Before thinning, 1968.

Site 905, Treatment D(4:20). After first thinning, 1968.

Site 905, Treatment D(4:20). After four thinnings, 2004.

Site 905, Treatment F(4:28)A. Before thinning, 1968.

Site 905, Treatment F(4:28)A. After first thinning, 1968.

Site 905, Treatment F(4:28). After four thinnings, 2004.

Site 929, Treatment I(0:0). 1970.

Site 929, Treatment I(0:0). 2004.


Site 929, Treatment A(3:18). Before thinning, 1970.


Site 929, Treatment A(3:18). After first thinning, 1970.


Site 929, Treatment A(3:18). After three thinnings, 2004.

Site 929, Treatment B(2:15). Before thinning, 1970.

Site 929, Treatment B(2:15). After first thinning, 1970.

Site 929, Treatment B(2:15). After two thinnings, 2004.

Site 929, Treatment C(1:10). After first thinning, 1970.

Site 929, Treatment C(1:10). After three thinnings, 2004.


Site 929, Treatment D(3:13). Before thinning, 1970.


Site 929, Treatment D(2:13). After first thinning, 1970.


Site 929, Treatment D(2:13). After three thinnings, 2004.

Site 929, Treatment F(3:18)A. Before thinning, 1970.

Site 929, Treatment F(3:13)A. After three thinnings, 2004.