Effect of Early Thinning on the Diameter Growth Distribution along the Stem of Scots Pine

Heli Peltola, Jari Miina, Ismo Rouvinen and Seppo Kellomäki

Peltola, H., Miina, J., Rouvinen, I. & Kellomäki, S. 2002. Effect of early thinning on the diameter growth distribution along the stem of Scots pine. Silva Fennica 36(4): 813–825.

The absolute and relative effects of the first thinning on the diameter growth distribution along the stems were studied in 98 Scots pines (*Pinus sylvestris* L.) at heights of 1.3, 4, 6 and 8 m. The data cover one 3-year pre-thinning period and four 3-year post-thinning periods in plots with densities varying from 575 to 3400 stems ha^{-1}. A shift in the point of maximum diameter growth down the bole was found during the first 3 years after thinning, with a shift back up the stem later. The thinning response over the whole 12-year post-thinning period was strongest the nearer the stem base and the heavier the thinning. The largest trees had the highest diameter growth after thinning in absolute terms, and the growth was greater the heavier the thinning. The absolute thinning response over the 12-year post-thinning period was highest in the medium tree size and in the largest trees, especially on the heavily thinned and lightly thinned plots. Whereas in the moderately thinned stand the smaller and larger trees responded more than did those of medium size on average. In relative sense, however, the small trees on heavily or moderately thinned plots responded more rapidly and more strongly than the medium-sized or large trees over the whole stem. The small trees on the lightly thinned plots responded only slightly to thinning. The results suggest that it is possible to affect the uniformity of wood properties (such as ring width) both within and between trees by thinning.

Keywords early thinnings, thinning responses, diameter growth, growth distribution, Scots pine
Correspondence *Peltola, Rouvinen* & *Kellomäki*, University of Joensuu, Faculty of Forestry, P.O. Box 111, FIN-80101 Joensuu, Finland; *Miina*, Finnish Forest Research Institute, Joensuu Research Centre, P.O. Box 68, FIN-80101 Joensuu, Finland
Fax +358 13 251 4444 **E-mail** heli.peltola@forest.joensuu.fi
Received 28 August 2001 **Accepted** 24 September 2002

1 Introduction

The absolute and relative growth responses of a tree to thinning can be defined respectively as the difference and ratio between the actual growth and the corresponding assumed growth if unaffected by thinning (Jonsson 1995). Both the measured growths of trees on unthinned control plots (Jonsson 1995) and the predicted growths computed by assuming harvested trees to be standing trees (Pukkala et al. 1998) have been used to represent unaffected growth.

In earlier studies, a diameter growth response near the stem base has been evident immediately after thinning (Vuokila 1960, Valinger 1992a, Tasissa and Burkhart 1997, Pukkala et al. 1998). No temporary growth decline (i.e. thinning stress) has been found at the stem base after thinning, but rather the diameter growth has increased more substantially in heavily thinned stands than in less severely thinned or unthinned ones (Hilt and Dale 1979, Thomson and Barclay 1984, Moschler et al. 1989, Tasissa and Burkhart 1997, Pukkala et al. 1998, Pape 1999). The thinning response diminishes with time, however (Hynynen 1995, Tasissa and Burkhart 1997).

On the other hand, the thinning response has been found to vary along the stem due to changes in the pattern of wood deposition (Farrar 1961, Myers 1963, Thomson and Barclay 1984, Tasissa and Burkhart 1997). The release of a tree from competition has the effect of producing a more tapered stem by virtue of greater stimulation of xylem production towards the base than at the upper levels immediately after thinning (Larson 1963, Kozlowski 1971, Barbour et al. 1992, Valinger 1992a, Tasissa and Burkhart 1997, Pape 1999). Thinning therefore directly affects the form and shape of the residual trees (Larson 1963, Arbaugh and Peterson 1993, Tasissa and Burkhart 1997).

A shift in the pattern of wood deposition down the stem following thinning and then back up the stem with time has been observed earlier by many authors (Vuokila 1960, Larson 1963, Myers 1963, Borosowski and Kolosowski 1971, Thomson and Barclay 1984, Valinger 1992a, Tasissa and Burkhart 1997). Borosowski and Kolosowski (1971), for example, argued that this shift of growth back up the stem would also be a response to increased stand closure after thinning. On the other hand, such a shift in growth could also be an effect of decreased wind sway as stand closure increases again (Jacobs 1939, 1954, Valinger 1992b). Diameter growth has been observed to increase most notably after thinning along the lowest third of the stem, while thinning has had either a slight positive effect or no effect on the middle stem and diameter growth at the top of the stem has even decreased compared with trees grown under unthinned conditions (Vuokila 1960, Forward and Nolan 1961, Valinger 1992a). Thus, trees in thinned stands tend to behave as open-grown trees, i.e. with a large radial growth in the lower part of the stem (Hartig 1870, 1891, Metzger 1896, Farrar 1961, Assmann 1970, Valinger 1992a).

Irrespective of stand density, the dominant and co-dominant trees with the best growing conditions and physiologically efficient crowns have a higher individual growth rate and more tapered stems than suppressed or intermediate trees, because they distribute more significant amounts of metabolites to the lower stem (Larson 1963, Kozlowski 1971, Tasissa and Burkhart 1997). On the other hand, dominant trees with large crowns in particular have been reported to show a minimal (relative) response to thinning, which merely helps them to maintain their rapid growth rate, while suppressed trees have shown a relatively greater response (Larson 1969, Pukkala et al. 1998). In absolute terms, however, dominant trees increase their diameter growth more than do suppressed trees. Furthermore, although suppressed trees could react more rapidly and strongly (in relative terms) to thinning than dominant trees, the decline in their growth is accordingly more sudden (Vuokila 1960, Larson 1969, Pukkala et al. 1998). Nyyssönen (1954), Niemistö (1994) and Pukkala et al. (1998) have argued earlier that both absolute and relative thinning responses in Scots pines (*Pinus sylvestris*), for example, are at their maximum among co-dominant and intermediate trees. In contrast, Jonsson (1974), Moore et al. (1994), Hynynen (1995) and Pape (1999) have suggested the same relative thinning response irrespective of tree size, especially among trees that were dominant at the time of thinning.

Thinning will affect growth, and consequently give rise to different wood properties, both by accelerating the growth rate of the trees and through selective removal (Persson et al. 1995, Pape 1999). Thus the thinning response and its dependence on tree size, growing space and changes in growing conditions form a body of highly relevant information for use in practical forest management, potentially allowing the timing and intensity of thinnings and the selection of trees for removal to be optimised in such a way that the desired thinning response in terms of wood quantity and quality could be obtained.

A variety of alternative approaches have been used so far to address thinning response of trees in forestry, i.e. from graphical and statistical analysis on the effects of thinning on ring width distribution (see Vuokila 1960, Farrar 1961, Forward and Nolan 1961, Myers 1963, Larson 1969, Kolowski 1971, Hilt and Dale 1979, Thomson and Barclay 1984, Moschler et al. 1989, Barbour et al. 1992, Valinger 1992a, Arbaugh and Peterson 1993, Niemistö 1994, Tasissa and Burkhart 1997, Pape 1999) into modelling such as covariance modelling (focus on within-tree variation) or mixed-effects modelling (focus on tree to tree variation) among others (see Hynynen 1995, Gregoire et al. 1995, Tasissa and Burkhart 1997, Herman et al. 1998, Pukkala et al. 1998). In the above context, this work was aimed at studying, based on both graphical and statistical analysis, the average absolute and relative effects of the post thinning stand density (not single tree level or within-tree variation) on the diameter growth distribution along the stems of 98 Scots pines (*Pinus sylvestris*) at heights of 1.3, 4, 6 and 8 m. The data cover one 3-year pre-thinning period and four 3-year post-thinning periods and apply to plots with densities varying from 575 to 3400 stems ha^{-1}. In the above context, the dependence of the diameter growth response on the post-thinning stand density and the tree size (diameter) at the time of thinning was studied along the stem.

2 Material and Methods

2.1 Site and Measurements

The data were derived from a long-term thinning experiment taking place close to the Mekrijärvi Research Station in North Karelia (62°47'N, 30°58'E, 145 m a.s.l.). The experiment was established in summer 1986 in a naturally regenerated stand of Scots pine (*Pinus sylvestris*) growing on a site with a rather poor nutrient supply (*Vaccinium* site type). The experiment employed ten plots of size 40 m by 30 m. The treatments were randomised: one plot was not thinned and nine were thinned from below to densities of 575 to 3400 stems ha^{-1} in winter 1986–1987 (Table 1). The experiment was designed to have a gradi-

Table 1. Stand characteristics of plots in the different stand density classes after thinning in 1986/87 and in 1997. N = number of stems ha^{-1}, G_{before} and G = stand basal area before and after thinning, respectively (m^{2}ha^{-1}), D = mean diameter at breast height (cm), H = mean height (m), T = mean breast height age (yrs), and g = weighted by tree basal area.

Stand density class, ha^{-1}	Plot	After thinning in 1986/87						in 1997		
		N ha^{-1}	G_{before} m^{2}ha^{-1}	G, m^{2}ha^{-1}	D_g, cm	H_g, m	T_g, yrs	G, m^{2}ha^{-1}	D_g, cm	H_g, m
<1000	3	575	13.2	5.1	10.9	9.0	21.5	11.3	16.3	11.9
	7	850	22.4	8.3	11.5	10.2	21.9	15.7	15.9	13.2
1000–2000	4	1200	20.6	11.3	11.5	9.9	23.0	19.7	15.3	13.0
	6	1492	20.1	12.7	11.0	9.6	23.2	21.2	14.1	12.9
	8	1800	21.7	14.5	10.9	9.5	22.4	23.6	14.0	13.4
2000–3000	10	2083	23.9	17.3	11.0	10.4	22.7	27.0	14.0	14.1
	5	2383	20.2	16.4	10.0	9.2	22.5	25.4	12.8	12.7
	9	2942	23.2	19.4	10.0	9.6	21.1	28.6	12.7	13.1
>3000	1	3400	25.1	22.9	10.2	9.8	21.5	32.4	13.2	13.4
	2	3683	22.2	22.2	10.7	9.6	20.2	27.8	13.0	13.0

ent of many thinning treatments. Each plot was surrounded by a 10-m buffer zone, which was treated in the same way as the plot. The mean breast height age of the stand at thinning was 22 years, and the initial basal area varied between 20 and 25 m^2ha^{-1}, with the exception that Plot 3 had a basal area of 13.2 m^2ha^{-1} (Table 1). The plots were re-measured ten years later, in 1997.

A total of 100 sample trees were chosen so as to mirror the between-tree variation in growth rates, i.e. the sample trees, 10 trees per plot, represented different diameter classes on the plot (three small, four medium-sized and three large trees were selected). These sample trees were felled in the autumns of 1998–1999 and cross-sectional discs were taken at fixed stem heights of 1.3, 4, 6 and 8 m. A wedge of wood 5 cm thick was sawn from each disc in a north-south direction for measurements of ring width. The ring widths of samples with a 12% moisture content (air dry) were determined by the image analysis technique WinDendro™ with an Agfa scanner (Regent Instruments Inc.). The ring widths were measured separately towards the south and north to the nearest 0.01 mm, working from the pith outwards, and the two sets of data were summed for the analysis of diameter growth.

2.2 Data Analysis

To analyse the effect of the post-thinning stand density on the average diameter growth at various heights (independent of tree size), the plots were placed in four classes according to the post-thinning stand density: plots <1000 stems ha^{-1} (i.e. heavy thinning, with 61–63% basal area removal), plots with 1000–2000 stems ha^{-1} (i.e. moderate thinning, with 33–45% removal), plots with 2000–3000 stems ha^{-1} (i.e. light thinning, with 16–28% removal) and plots with >3000 stems ha^{-1} (i.e. no thinning). The plots in the densest class are regarded here as unthinned, although in practice Plot 2 was unthinned and Plot 1 was very lightly thinned, but with 9% basal area removal of dead and dying trees (Table 1). Although not fully correct expectation, the density classes after thinning were considered to be merely produced by thinning. However, the mean diameter at breast height (dbh) of the sample trees at thinning was almost the same in the various stand density classes, i.e. 9.1±1.3, 9.5±1.8, 9.0±1.9 and 9.3±2.1 cm from sparsest to densest, and the mean heights were 9.3±1.1, 9.7±0.9, 9.8±1.0 and 9.7±1.1 m, respectively.

To analyse the thinning responses of trees of different size (diameter), the sample trees within each stand density class were classified into three dbh classes (dbh1, dbh2, dbh3) according to their diameter at the time of thinning. Dbh1 consisted of trees with a diameter of 5.5–7.9 cm (3, 5, 9 and 6 trees, from the sparsest stand to the densest one), dbh2 trees with a diameter of 8.0–10.4 cm (13, 15, 15 and 8 trees), and dbh3 trees with a diameter of 10.5–13+ cm (4, 10, 5 and 5 trees). The ranges of dbh classes were selected so that the sample trees within each stand density class were distributed into the dbh classes as evenly as possible. Thus two trees with a dbh less than 5.5 cm were rejected from the two densest classes because there were no trees as small as this in the other stand density classes. All the analyses were thus carried out for a total of 98 sample trees.

The data consisted of the annual diameter increments over the period 1984–1998, grouped into 3-year periods for analysis purposes: the first period from 1984–1986 representing the pre-thinning growth and the following ones subsequent post-thinning growth periods. In a pre-analysis of the data it was found that there were no statistically significant differences ($p<0.05$) in average pre-thinning diameter growth (years 1984–86) between the stand density classes (independent of tree size), except at the 8 m height level (see Results, Table 2), where that on the heavily thinned plots (<1000 ha^{-1}) was significantly lower than on the unthinned (>3000 ha^{-1}) or moderately (1000–2000 ha^{-1}) thinned plots. Similarly, there were no statistically significant differences in average pre-thinning diameter growth (years 1984–86) between the trees of different size in the stand density classes, except at 4 m height and dbh 10.5–13+ cm and at 8 m and dbh 8–10.4 cm (see Results, Tables 3 and 4). This was expected to provide a good basis for comparing the absolute and relative thinning responses, in which, firstly, the diameter growths for the same growth period and height were compared between the post-thinning stand density classes in order to study the average diameter growth response to thinning. Secondly, the diameter growths for the same growth period, height and diameter class (dbh1–dbh3) were compared between the post-thinning stand density classes to study the thinning responses of trees of different size (diameter).

The study design was pseudo-replicated, because there were several trees measured from each plot, i.e. trees were not independent observations. It was possible to include the correlations in the analysis using a mixed modelling approach, and therefore, a mixed linear model with random plot factor was fitted for the total post-thinning diameter growth at breast height using post-thinning stand density and tree diameter as predictors. However, the random plot factor was not significant suggesting that also the within-plot correlation could be negligible and thus analysis of variance was justified. Thereafter, the statistical significance of the differences between treatments was studied with the help of one-way analysis of variance (SPSS Inc. 2000). The pairwise multiple comparisons between stand density classes were performed using the LSD (least significant difference) PostHoc test, because the data was found homogeneous (according to the test of homogeneity of variances). If the level of significance of a statistical analysis was less than 0.05, the difference was called significant.

Variation in annual climatic factors was not taken into account, because comparisons were not made between growth periods, and in any case calculation in terms of 3-year growth periods smoothes out most of the annual growth variation. The averages of the annual growth indices based on the diameter growth of all trees on the unthinned plot varied between 98–102 for the 3-year growth periods (Pukkala et al. 2002).

3 Results

3.1 Average Thinning Response

In the unthinned plots, the post-thinning diameter growth decreased as a function of ring age at every height level, as could be expected (Fig. 1, Table 2), while the diameter growth on the thinned plots showed a clear thinning response (Table 2). The timing and magnitude of the diameter growth response varied along the stem. During the first 3 years after thinning (1987–1989), the diameter growth increased markedly only near the stem base, so that at breast height level (1.3 m), the figure was on average 16% higher on the lightly thinned plots (2000–3000 ha^{-1}) than on

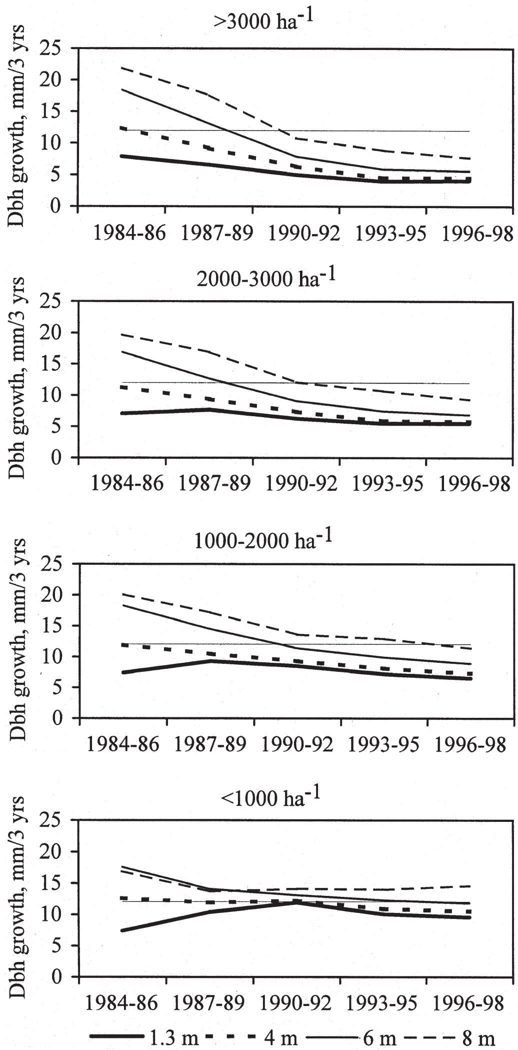

Fig. 1. Diameter growth (mm) at different stem heights by post-thinning stand density classes >3000 ha^{-1}, 2000–3000 ha^{-1}, 1000–2000 ha^{-1} and <1000 ha^{-1}. The horizontal thin line is the maximal 3-year diameter growth for desirable wood quality (i.e. ring width < 2 mm) used by Uusvaara (1985).

Table 2. Diameter growth (mm) at given heights in the stand density classes over the five measurement periods. Relative diameter growth (%) by comparison with the unthinned plots (>3000 ha^{-1}) is given in parenthesis. The period 1984–86 represents the 3-year diameter growth before thinning, and the period 1987–98 the total post-thinning diameter growth.

Height and stand density class	Diameter growth (mm) over measurement periods 1984–86	1987–89	1990–92	1993–95	1996–98	1987–98
1.3 m						
>3000 ha^{-1}	7.9^{a} (100)	6.6^{a} (100)	5.0^{a} (100)	4.0 (100)	4.1 (100)	19.6 (100)
2000–3000 ha^{-1}	7.1^{a} (90)	7.7 ^{a} (116)	6.3^{a} (127)	5.5 (139)	5.5^{a} (134)	24.9 (127)
1000–2000 ha^{-1}	7.4^{a} (94)	9.3^{b} (140)	8.5 (170)	7.2 (182)	6.5^{a} (159)	31.4 (160)
< 1000 ha^{-1}	7.4^{a} (94)	10.4^{b} (158)	11.9 (239)	10.1 (255)	9.6 (236)	42.0 (214)
4 m						
>3000 ha^{-1}	12.4^{a} (100)	9.2^{a} (100)	6.3^{a} (100)	4.5 (100)	4.5 (100)	24.5^{a} (100)
2000–3000 ha^{-1}	11.3^{a} (91)	9.4^{a} (103)	7.4^{a} (117)	5.9 (131)	5.8 (128)	28.5^{a} (116)
1000–2000 ha^{-1}	11.9^{a} (96)	10.5^{ab} (114)	9.3 (148)	8.1 (178)	7.3 (162)	35.2 (144)
< 1000 ha^{-1}	12.6^{a} (102)	11.9^{b} (130)	12.2 (195)	10.9 (240)	10.5 (230)	45.4 (185)
6 m						
>3000 ha^{-1}	18.4^{a} (100)	13.1^{ab} (100)	7.9^{a} (100)	5.9 (100)	5.6^{a} (100)	32.5^{a} (100)
2000–3000 ha^{-1}	16.9^{a} (92)	12.7 ^{a} (97)	9.1^{a} (115)	7.5 (127)	6.9^{a} (124)	36.2^{a} (111)
1000–2000 ha^{-1}	18.3^{a} (99)	14.5^{b} (111)	11.4 (114)	9.9 (168)	8.9 (160)	44.8 (138)
< 1000 ha^{-1}	17.6^{a} (95)	14.1^{ab} (107)	13.1 (165)	12.3 (209)	11.8 (212	51.3 (158)
8 m						
>3000 ha^{-1}	21.9^{a} (100)	17.6^{a} (100)	10.8^{a} (100)	8.9 (100)	7.7^{a} (100)	45.0^{a} (100)
2000–3000 ha^{-1}	19.7^{ab} (90)	16.9^{a} (96)	12.1^{ab} (112)	10.7 (121)	9.3^{a} (120)	48.9^{ab} (109)
1000–2000 ha^{-1}	20.1^{a} (92)	17.2^{a} (97)	13.6^{bc} (126)	12.9^{a} (146)	11.4 (147)	55.1^{bc} (122)
< 1000 ha^{-1}	16.9^{b} (77)	13.7 (78)	14.1^{c} (130)	14.0^{a} (158)	14.6 (189)	56.3^{c} (125)

Note: Data for the same period and height not marked with the same letter are significantly different ($p<0.05$). The differences were tested between density classes within heights along the stem.

the unthinned plots (Table 2), the corresponding percentages for the moderately thinned (1000–2000 ha^{-1}) and heavily thinned plots (<1000 ha^{-1}) being 40% and 58%. The diameter growth immediately after thinning was thus significantly higher in these two sparsest classes than in the two densest classes. The response of diameter growth at the 4 and 6 m height levels to thinning was slight but not significant during the first 3-year post-thinning period, while at 8 m, thinning even reduced the diameter growth especially, if heavy (Table 2).

During the second 3-year period (1990–92), the diameter growth response to thinning was significant up to a height of 6 m on the stem, except in the lightly thinned plots, which did not differ from the unthinned ones (Table 2). Thus a shift in the diameter growth distribution back up the stem with time was observed. During the third 3-year period (1993–95), all the differences in the mean diameter growth of trees between the stand density classes were significant, except for the difference between the two sparsest classes at a height of 8 m. During this period, i.e. 7–9 years after thinning, the diameter growth response to thinning was at its maximum at 1.3, 4 and 6 m. The highest relative thinning response was recorded in the diameter growth of the trees on the most heavily thinned plots, which was 155%, 140% and 109% higher than on the unthinned plots at heights of 1.3 m, 4 m and 6 m, respectively (Table 2). At 8 m, the growth response still seemed to be increasing or to have remained at the same level during the next 3-year period. During the last measurement period (1996–98), most of the differences between the thinned and unthinned plots remained significant, although the thinning response started to diminish, except at 6 and 8 m in the heavily thinned plots, where it still increased.

The thinning response over the whole 12-year post-thinning period was stronger nearer

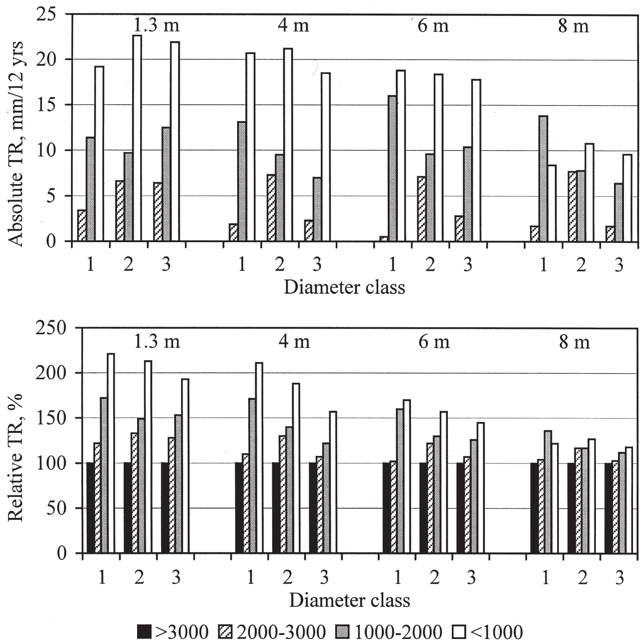

Fig. 2. Absolute (up) and relative (below) diameter growth responses (TR) by comparison with the unthinned plots (>3000 ha^{-1}) in three diameter classes (1 = 5.5–7.9 cm; 2 = 8.0–10.4 cm; 3 = 10.5–13+ cm) at different stem heights over the 12-year post-thinning period.

to the stem base and the heavier the thinning. The maximum relative thinning response was recorded at a height of 1.3 m in the most heavily thinned plots (114% higher diameter growth than on the unthinned plot). This means that thinning increased the growth in breast height diameter in these trees by an average of 1.9 mm a^{-1}, which was also the maximum absolute thinning response recorded.

3.2 Thinning Response in Different Diameter Classes

In each diameter class a significant response during the first 3 years after thinning (1987–89) was observed only at heights of 1.3 and 4 m on heavily thinned plots (Table 3). Later on the thinning response was significant regardless of tree size on the moderately thinned plots as well and higher on the stem (Tables 3 and 4). The growth response was generally at its maximum 7–9 years after thinning regardless of tree size. But in the case of large trees, and especially higher on the stem, the maximum response was later than that.

The large trees (dbh 10.4–13+ cm) had the highest diameter growth in absolute terms in all the stand density classes, and the medium-sized trees (dbh 8–10.5 cm) also grew better in diameter than the small trees (dbh 5.5–7.9 cm) over the whole 12-year post-thinning period. Furthermore, the total absolute thinning response was significant at heights of up to 6 m on the heavily thinned (<1000 ha^{-1}) and moderately thinned plots (1000–2000 ha^{-1}) for all tree sizes (small, medium-sized and large), but not on the lightly thinned plots (2000–3000 ha^{-1}). At a height of 8 m, only the diameter growth of the medium-sized trees growing in heavily thinned plots was significantly greater than that observed on the unthinned plots.

Both the absolute and relative thinning responses over the 12-year post-thinning period were higher the more intensive the thinning was, regardless of tree size (Fig. 2). The differences in

Table 3. Diameter growth (mm) at heights of 1.3 and 4 m in the diameter and stand density classes over the given measurement periods. Relative diameter growth (%) by comparison with the unthinned plots (>3000 ha^{-1}) during the same period is given in parenthesis.

Height, diameter and stand density class	Diameter growth (mm) over measurement periods 1984–86	1987–89	1990–92	1993–95	1996–98	1987–98
1.3 m						
dbh1 (5.5–7.9 cm)						
>3000 ha^{-1}	8.0^{a} (100)	5.9^{a} (100)	4.1^{a} (100)	3.0^{a} (100)	2.9^{a} (100)	15.9^{a} (100)
2000–3000 ha^{-1}	5.9^{a} (73)	5.6^{a} (95)	4.8^{a} (118)	4.4^{ab} (146)	4.5^{ab} (157)	19.3^{ab} (122)
1000–2000 ha^{-1}	6.0^{a} (75)	8.0^{ab} (135)	7.9^{b} (190)	6.4^{bc} (213)	5.2^{bc} (180)	27.3^{bc} (172)
<1000 ha^{-1}	7.1^{a} (89)	9.8^{b} (166)	10.4^{b} (254)	8.0^{c} (267)	6.8^{c} (234)	35.1^{c} (221)
dbh2 (8–10.4 cm)						
>3000 ha^{-1}	7.0^{a} (100)	6.4^{a} (100)	5.0^{a} (100)	4.1^{a} (100)	4.5^{a} (100)	20.0^{a} (100)
2000–3000 ha^{-1}	7.5^{a} (108)	8.3^{a} (129)	6.9^{ab} (137)	5.7^{ab} (139)	5.7^{a} (129)	26.6^{ab} (133)
1000–2000 ha^{-1}	6.8^{a} (97)	8.6^{ab} (135)	8.0^{b} (161)	6.7^{b} (161)	6.4^{a} (143)	29.7^{b} (149)
<1000 ha^{-1}	7.5^{a} (107)	10.7^{b} (167)	11.8 (236)	10.3 (250)	9.9 (223)	42.6 (213)
dbh3 (10.5–13+ cm)						
>3000 ha^{-1}	9.3^{a} (100)	7.8^{a} (100)	6.0^{a} (100)	4.8^{a} (100)	4.9^{a} (100)	23.4^{a} (100)
2000–3000 ha^{-1}	8.1^{a} (86)	9.5^{ab} (122)	7.4^{ab} (123)	6.8^{ab} (142)	6.3^{ab} (129)	30.0^{ab} (128)
1000–2000 ha^{-1}	9.1^{a} (97)	10.8^{b} (140)	9.4^{b} (157)	8.4^{b} (175)	7.3^{b} (150)	35.9^{bc} (153)
<1000 ha^{-1}	7.5^{a} (80)	10.1^{ab} (131)	13.3 (222)	11.0 (230)	10.8 (222)	45.3^{c} (193)
4 m						
dbh1 (5.5–7.9 cm)						
>3000 ha^{-1}	11.1^{a} (100)	7.5^{ab} (100)	4.4^{a} (100)	3.3^{a} (100)	3.4^{a} (100)	18.6^{a} (100)
2000–3000 ha^{-1}	9.0^{a} (81)	6.8^{b} (90)	5.1^{a} (116)	4.3^{a} (131)	4.4^{ab} (130)	20.5^{a} (110)
1000–2000 ha^{-1}	11.4^{a} (103)	9.5^{ac} (126)	8.6^{b} (196)	7.4^{b} (225)	6.2^{bc} (183)	31.7^{b} (171)
<1000 ha^{-1}	12.1^{a} (109)	10.7^{c} (143)	11.5^{b} (261)	8.7^{b} (264)	8.4^{c} (247)	39.3^{b} (211)
dbh2 (8–10.4 cm)						
>3000 ha^{-1}	11.8^{a} (100)	8.5^{a} (100)	6.2 (100)	4.6 (100)	4.8^{a} (100)	24.0 (100)
2000–3000 ha^{-1}	12.3^{a} (105)	10.2^{ab} (120)	8.3^{a} (135)	6.5^{a} (141)	6.3^{ab} (131)	31.3^{a} (130)
1000–2000 ha^{-1}	11.1^{a} (94)	9.8^{ab} (115)	8.9^{a} (144)	7.8^{a} (172)	7.0^{b} (147)	33.5^{a} (140)
<1000 ha^{-1}	12.8^{a} (108)	11.7^{b} (138)	11.6 (187)	11.1 (241)	10.7 (223)	45.2 (188)
dbh3 (10.5–13+ cm)						
>3000 ha^{-1}	14.8^{a} (100)	12.2^{a} (100)	8.6^{a} (100)	5.9^{a} (100)	5.6^{a} (100)	32.4^{a} (100)
2000–3000 ha^{-1}	12.2^{b} (82)	12.0^{a} (98)	8.4^{a} (98)	7.2^{ab} (121)	7.1^{ab} (127)	34.7^{a} (107)
1000–2000 ha^{-1}	13.4^{ab} (91)	12.0^{a} (98)	10.2^{a} (118)	8.8^{b} (148)	8.4^{b} (151)	39.4^{a} (122)
<1000 ha^{-1}	12.7^{ab} (86)	13.5^{a} (110)	14.7 (170)	11.7 (197)	11.1 (199)	50.9 (157)

Note: Data for the same period, height and diameter class not marked with the same letter are significantly different ($p<0.05$). The differences were tested between density classes within dbh-classes and heights along the stem.

absolute and relative thinning responses between trees of different size and in different stand density classes were most evident near the stem base (1.3 m), whereas higher up the stem the differences diminished. The absolute thinning response at stem base over the 12-year post-thinning period was highest in the medium-sized and large trees on the most heavily thinned plots and also on the most lightly thinned ones (see Fig. 2), whereas on the moderately thinned plots the small and large trees responded more than medium-sized ones did. In relative terms, the small trees on both the heavily and moderately thinned plots responded more rapidly and strongly than did the medium-sized or large trees over the whole stem, but on the lightly thinned plots the small trees responded only slightly to thinning.

Table 4. Diameter growth (mm) at heights of 6 and 8 m in the diameter and stand density classes over the given measurement periods. Relative diameter growth (%) by comparison with the unthinned plots (>3000 ha^{-1}) during the same period is given in parenthesis.

Height, diameter and stand density class	Diameter growth (mm) over measurement periods 1984–86	1987–89	1990–92	1993–95	1996–98	1987–98
6 m						
dbh1 (5.5–7.9 cm)						
>3000 ha^{-1}	17.0^{a} (100)	11.6^{ab} (100)	6.3^{a} (100)	4.5^{a} (100)	4.3^{a} (100)	26.7^{a} (100)
2000–3000 ha^{-1}	14.4^{a} (85)	9.6^{a} (83)	6.6^{a} (104)	5.7^{a} (126)	5.3^{a} (124)	27.2^{a} (102)
1000–2000 ha^{-1}	17.4^{a} (102)	14.1^{b} (121)	11.2^{b} (178)	9.6^{b} (213)	7.9^{b} (184)	42.7^{b} (160)
<1000 ha^{-1}	15.4^{a} (91)	11.7^{ab} (101)	12.8^{b} (203)	10.9^{b} (242)	10.2^{b} (237)	45.5^{b} (170)
dbh2 (8–10.4 cm)						
>3000 ha^{-1}	17.8^{a} (100)	12.4^{a} (100)	8.0 (100)	6.2^{a} (100)	5.8^{a} (100)	32.4^{a} (100)
2000–3000 ha^{-1}	18.3^{a} (103)	13.7^{a} (110)	10.3^{a} (128)	8.1^{ab} (131)	7.5^{ab} (129)	39.5^{ab} (122)
1000–2000 ha^{-1}	16.7^{a} (94)	13.2^{a} (106)	10.8^{ab} (135)	9.6^{b} (155)	8.4^{b} (146)	42.0^{b} (130)
<1000 ha^{-1}	18.1^{a} (102)	14.1^{a} (114)	12.4^{b} (155)	12.3 (198)	12.0 (209)	50.8 (157)
dbh3 (10.5–13+ cm)						
>3000 ha^{-1}	21.2^{a} (100)	16.1^{a} (100)	9.7^{a} (100)	7.2^{a} (100)	6.8^{a} (100)	39.7^{a} (100)
2000–3000 ha^{-1}	17.5^{a} (83)	15.4^{a} (96)	10.2^{a} (106)	8.9^{ab} (124)	8.0^{ab} (117)	42.5^{ab} (107)
1000–2000 ha^{-1}	21.0^{a} (99)	16.8^{a} (105)	12.5 (129)	10.7^{b} (149)	10.1^{b} (149)	50.1^{bc} (126)
<1000 ha^{-1}	17.6^{a} (83)	15.9^{a} (99)	15.5 (160)	13.3 (186)	12.7 (187)	57.5^{c} (145)
8 m						
dbh1 (5.5–7.9 cm)						
>3000 ha^{-1}	20.0^{a} (100)	15.9^{a} (100)	8.8^{a} (100)	6.9^{a} (100)	6.5^{a} (100)	38.0^{a} (100)
2000–3000 ha^{-1}	16.2^{a} (81)	14.5^{a} (91)	9.5^{ab} (108)	8.4^{ab} (122)	7.4^{a} (114)	39.7^{a} (104)
1000–2000 ha^{-1}	16.8^{a} (84)	15.9^{a} (101)	11.3^{ab} (129)	12.9^{c} (188)	11.6^{b} (179)	51.8^{a} (136)
<1000 ha^{-1}	10.3^{a} (52)	9.3 (58)	12.6^{b} (143)	11.0^{bc} (159)	13.5^{b} (209)	46.4^{a} (122)
dbh2 (8–10.4 cm)						
>3000 ha^{-1}	22.1^{a} (100)	17.3^{a} (100)	10.6^{a} (100)	8.9 (100)	7.7 (100)	44.5^{a} (100)
2000–3000 ha^{-1}	20.5^{a} (93)	17.3^{a} (100)	13.0^{ab} (122)	11.6^{a} (130)	10.2^{a} (133)	52.2^{ab} (117)
1000–2000 ha^{-1}	18.7^{ab} (84)	16.2^{ab} (94)	13.2^{b} (125)	12.3^{ab} (137)	10.6^{a} (138)	52.3^{ab} (117)
<1000 ha^{-1}	16.6^{b} (75)	13.7^{b} (79)	13.4^{b} (126)	14.4^{b} (162)	14.8 (192)	56.3^{b} (127)
dbh3 (10.5–13+ cm)						
>3000 ha^{-1}	23.1^{a} (100)	20.2^{a} (100)	13.5^{a} (100)	11.1^{a} (100)	9.3^{a} (100)	54.2^{a} (100)
2000–3000 ha^{-1}	23.5^{a} (102)	20.0^{a} (99)	13.9^{a} (102)	12.1^{ab} (109)	9.9^{a} (106)	55.9^{a} (103)
1000–2000 ha^{-1}	23.7^{a} (103)	19.1^{a} (94)	15.1^{ab} (112)	14.0^{b} (126)	12.4 (133)	60.6^{a} (112)
<1000 ha^{-1}	21.1^{a} (91)	16.8^{a} (83)	17.3^{b} (128)	14.8^{b} (133)	14.9 (159)	63.8^{a} (118)

Note: Data for the same period, height and diameter class not marked with the same letter are significantly different ($p<0.05$). The differences were tested between density classes within dbh-classes and heights along the stem.

4 Discussion and Conclusions

The aim here was to analyse the effects of post-thinning stand density (and thus thinning intensity) on the diameter growth distribution along the stem of Scots pine over a period of 12 years after thinning. The results indicated that the increase in diameter growth immediately after thinning was most marked at breast height and in the heavily thinned plots, while thinning had only a slight effect at heights of 4 and 6 m in the stem, and even reduced the diameter growth at 8 m. This was probably due to a shift in the point of maximum growth down the bole following thinning, as was also found earlier by Vuokila (1960), Valinger (1992a) and Tasissa and Burkhart (1997). Tasissa and Burkhart (1997), for example, reported that thinning effects in *Pinus taeda* were not evident during the first 3-year period after thinning except near the stem base, while according to Vuokila

(1960), the growth increase brought about by thinning was most marked along the lowest third of the stem, whereas in the middle stem thinning had either a slight effect or was entirely meaningless, and in the top of the stem it could even reduce growth. Valinger (1992a) also found in Scots pine that there was an increase in radial growth in the lower part of the stem immediately after thinning, but that it was less in the upper stem. Similar results had been reported earlier for the red pine (*Pinus resinosa*) by Forward and Nolan (1961) and for Norway spruce (*Picea abies*) by Assmann (1970).

A shift back up the stem with time was nevertheless observed in the pattern of diameter growth during the following 3-year periods after thinning. Myers (1963), for example, observed this same shift down the stem in the ponderosa pine (*Pinus ponderosa*) following thinning and then back up the stem later, and similar patterns have been reported in the Scots pine (*Pinus sylvestris*) by Vuokila (1960) and Valinger (1992a), in the Douglas fir (*Pseudotsuga menziesii*) by Thomson and Barclay (1984) and in the loblolly pine (*Pinus taeda*) by Tasissa and Burkhart (1997). During the last 3-year period, i.e. 9–12 years after thinning, the response still remained significant, although it tended to diminish, especially in the lower parts of the stem. This is in line with the results of Tasissa and Burkhart (1997), who found in *Pinus taeda* that the effect of thinning had not diminished to the pre-treatment level by the end of the 12-year period studied.

On the whole, the results also indicated that the diameter growth increased more substantially on the heavily thinned plots than on the less intensively thinned or unthinned plots, and more so near the stem base than further up the stem. Thus thinning intensity appears to have less influence on diameter growth towards the tree top. Both Tasissa and Burkhart (1997) and Moschler et al. (1989) found in *Pinus taeda* that radial growth increased more on heavily thinned plots than on less intensively thinned or unthinned (control) plots, and Pape (1999) made the same observations in *Picea abies* and Pukkala et al. (1998) in the Scots pine.

Moderate and heavy thinning increased the diameter growth of all tree size (diameter) classes significantly compared with the trees on the unthinned plots (both in absolute and relative terms). The large trees had the highest diameter growth in absolute terms, but the medium-sized trees also grew better than the small ones over the 12-year post-thinning period regardless of the stand density class. Furthermore, the absolute thinning response (i.e. the difference between growth affected and unaffected by thinnings) over the 12-year post-thinning period was highest at the stem base (1.3 m) of the medium-sized and large trees on the most heavily thinned plots and also on the lightly thinned plots, whereas on the moderately thinned plots the small and large trees responded more than did the medium-sized ones.

In relative terms, however, the small trees on the heavily and moderately thinned plots responded more rapidly and strongly over the whole length of the stem than the medium-sized or large ones, although the small trees on the lightly thinned plots responded only slightly to thinning. Both the absolute and relative thinning responses over the whole 12-year post-thinning period were higher the more intensive the thinning was, regardless of tree size. The differences in absolute and relative thinning responses between trees of different size (and in different stand density classes) were most evident near the stem base, whereas they diminished higher up the stem.

Furthermore, the post-thinning diameter growth was higher than the pre-thinning diameter growth only at the stem base. The diameter growth of the trees in heavily thinned plots during the last 3-year period was still above the pre-treatment growth level in the two largest diameter classes. In line with earlier findings reported by Tasissa and Burkhart (1997), for example, the differences in growth pattern between the trees subject to more intense competition and those subject to less competition were most evident near the stem base. Thus the large (dominant and co-dominant) trees with the best growing conditions and physiologically efficient crowns had a higher individual growth rate and more tapered stems than the smaller (suppressed and intermediate) trees (Larson 1963, Kozlowski 1971, Tasissa and Burkhart 1997).

Similar results have been observed in many earlier studies, i.e. large (dominant) trees with large crowns have been reported to show less response to thinning in relative terms, while smaller (suppressed) trees have shown a greater relative response (see Vuokila 1960, Larson 1969, Pukkala et al. 1998). Although small trees have been found to react more rapidly and strongly to thinning than large ones, the decline in growth in small trees has been correspondingly more sudden. Earlier, Pukkala et al. (1998) also found both the absolute and relative 5-year thinning responses to be at their maximum among co-dominant and medium-sized Scots pines, while the relative thinning response was at its minimum among the largest trees. This is also in accordance with the results reported by Nyyssönen (1954) and Niemistö (1994).

The large variation in diameter growth, and thus as a consequence also in other wood properties, existing between trees offers an opportunity to improve wood properties through silviculture, by favouring trees which are expected to have desirable raw material properties. It also seems to be possible to affect the uniformity of wood properties within trees by proper silvicultural practices, in that Uusvaara (1985) maintains that an increase in the width of annual rings, and thus in growth rate, detracts from the quality of the timber. Distinct correlations have also been demonstrated between annual ring width in the vicinity of the pith and the internal knottiness of the wood, wood density and quality and strength of sawlogs and sawn timber (Heiskanen 1965, Uusvaara 1985). The percentage of high quality sawn pieces will decrease and the proportion of poorer qualities increase as the annual rings become wider in the vicinity of the pith (Uusvaara 1985). According to Heiskanen (1965), the most noticeable changes in the quality of timber take place between the annual ring thickness of 3 and 2 mm. It has been argued that the quality of sawn timber is highest at a growth ring width of about 2 mm, and once the width around the pith rises to 3.5 mm there is hardly any most valuable sawn timber to be obtained, although the quality also decreases at exceptionally low annual ring widths of 0.5 to 1.5 mm (Uusvaara 1985).

If a maximum ring width of 2 mm had been used as a wood quality criterion in this study, the thinning practices applied in the heavily thinned plots would not have been classed as desirable, as the annual rings all along the stem would have been more or less 2 mm wide at least during the whole post-thinning period (see Fig. 1). On the other hand, a higher uniformity in ring width was found along the stem in the most heavily thinned plots than in less severely thinned ones. Furthermore, medium-sized trees could provide best quality in this respect, too. The present results, however, would not alone enable any silvicultural recommendations to be given on when and how stands should be thinned in order to obtain the desired response in terms of wood quantity and quality, i.e. more research would be needed. But, the results suggest that it is possible to affect the uniformity of wood properties such as ring width both within and between trees by thinning.

Acknowledgements

This work was funded through the WOOD WISDOM Research Programme promoted by the Academy of Finland (1998–2001), under the project “Effects of silvicultural management on the physical and chemical properties of wood” (Project no. 62014), led by Dr Heli Peltola, Faculty of Forestry, University of Joensuu. This project belongs to the consortium on the “Effects of forest management on wood quality”, co-ordinated by Dr Pekka Saranpää, Finnish Forest Research Institute. The work is also related to that being carried out under the Finnish Centre of Excellence Programme (2000–2005) at the Centre of Excellence for Forest Ecology and Management (Project no. 64308), co-ordinated by Prof. Seppo Kellomäki, Faculty of Forestry, University of Joensuu. The support provided by the Academy of Finland, the National Technology Agency (Tekes) and the University of Joensuu is gratefully acknowledged. The authors would also like to thank Mr Jarmo Pennala for carrying out the laboratory work and Mr Malcolm Hicks for revising the English of the manuscript.

References

Arbaugh, M.J. & Peterson, D.L. 1993. Stemwood production patterns in ponderosa pine: effects of stand dynamics and other factors. USDA Forestry Service Research Papers PSW-RP-217.

Assmann, E. 1970. The principles of forest yield study: studies in the organic production, structure, increment and yield of forest stands. Pergamon Press, Oxford. 506 p.

Barbour, R.J., Bailey, R.E. & Cook, J.A. 1992. Evaluation of relative density, diameter growth and stem form in a red spruce (Picea rubens) stand 15 years after precommercial thinning. Canadian Journal of Forest Research 22: 229–238.

Borosowski, M. & Kolosowski, K. 1971. The effect of light admittance to a pine stand on the distribution of thickness increment along tree stems. Sylwan 5: 13–23. (In Polish with English summary.)

Farrar, J.L. 1961. Longitudinal variation in the thickness of the annual ring. Forestry Chronicle 37: 323–330.

Forward, D.F. & Nolan, N.J. 1961. Growth and morphogenesis in the Canadian forest species. Radial growth in branches and main axis of Pinus resinosa Ait. under conditions of open growth, suppression, and release. Canadian Journal of Botany 39: 385–409.

Gregoire, T.G., Schabenberger, O. & Barrett, J.P. 1995. Linear modelling of irregularly spaced, unbalanced, longitudinal data from permanent plot measurements. Canadian Journal of Forest Research 25: 137–156.

Hartig, R. 1870. Zum Lehre vom Dickenwachstum der Waldbäume. Botanische Zeitung 28: 505–513, 521–529. (In German)

— 1891. Lerbuch der Anatomie und Physiologie der Pflanzen. J. Springer, Berlin. 308 p. (In German)

Heiskanen, V. 1965. On the relations between the development of the early age and thickness of trees and their branchiness in pine stands. Acta Forestalia Fennica 80(2): 1–62. (In Finnish with English summary)

Herman, M., Dutilleul, P. & Avella-Shaw, T. 1998. Growth rate effects on temporal trajectories of ring width, wood density, and mean tracheid length in Norway spruce (Picea abies (L.) Karst.). Wood and Fiber Science 30(1): 6–17.

Hilt, D.E. & Dale, M.E. 1979. Stem form changes in upland oaks after thinning. USDA Forestry Service Research Papers NE-433.

Hynynen, J. 1995. Predicting the growth response to thinning for Scots pine stands using individual-tree growth models. Silva Fennica 29: 225–246.

Jacobs, M.R. 1939. A study on the effects of sway on trees. Australian Commonwealth Forestry Bureau, Bulletin 26: 1–19.

— 1954. The effect of wind sway on the form and development of Pinus radiata D. Don. Australian Journal of Botany 2: 35–51.

Jonsson, B. 1974. The thinning response of Scots pine (Pinus silvestris) in northern Sweden. The Royal College of Forestry, Department of Forest Yield Research, Research Notes 28. 41 p.

— 1995. Thinning response functions for single trees of Pinus sylvestris L. and Picea abies (L.) Karst. Scandinavian Journal of Forest Research 10: 353–369.

Kozlowski, T.T. 1971. Growth and development of trees. Vol. 2 Cambial growth, root growth, and reproductive growth. Academic Press, New York and London. 514 p.

Larson, P. 1963. Stem form development of forest trees. Forest Science Monographs 5. 42 p.

— 1969. Wood formation and the concept of wood quality. Yale University, School of Forestry and Environmental Studies, Bulletin 74: 1–54.

Metzger, K. 1896. Form und Wachstum der Waldbäume im Lichte der Darwinschen Lehre. Allgemeine Forst- und Jagdzeitung 72: 224–233. (In German)

Moore, J.A., Lianjun, Z. & Newberry, J.D. 1994. Effects of intermediate silvicultural treatments on the distribution of within-stand growth. Canadian Journal of Forest Research 24: 398–404.

Moschler, W.W., Dougal, E.F. & McRae, D.D. 1989. Density and growth ring characteristics of Pinus taeda L. following thinning. Wood and Fiber Science 21(3): 313–319.

Myers, C.A. 1963. Vertical distribution of annual increment in thinned ponderosa pine. Forest Science 9: 394–404.

Niemistö, P. 1994. Männikön ensiharvennus ala-, ylä- tai laatuharvennusta käyttäen. Folia Forestalia 1994: 19–32. (In Finnish)

Nyyssönen, A. 1954. On the structure and development of Finnish pine stands treated with different cuttings. Acta Forestalia Fennica 60(4): 1–194. (In Finnish with English summary)

Pape, R. 1999. Influence of thinning and tree diameter class on the development of basic density and annual ring width in Picea abies. Scandinavian Journal of Forest Research 14: 27–37.

Persson, B., Persson, A., Ståhl, E.G. & Karlmats, U. 1995. Wood quality of Pinus sylvestris progenies at various spacings. Forest Ecology and Management 76: 127–138.

Pukkala, T., Miina, J. & Kellomäki, S. 1998. Response to different thinning intensities in young Pinus sylvestris. Scandinavian Journal of Forest Research 13: 141–150.

— , Miina, J. & Palahí, M. 2002. Thinning response and thinning bias in a young Scots pine stand. Silva Fennica 36(4): 827–840.

SPSS Inc. 2000. SPSS base 10.0 user's guide. 537 p.

Tasissa, G. & Burkhart, H.E. 1997. Modeling thinning effects on ring width distribution in loblolly pine (Pinus taeda). Canadian Journal of Forest Research 27: 1291–1301.

Thomson, A.J. & Barclay, H.J. 1984. Effects of thinning and urea fertilization on the distribution of area increment along the bole of Douglas-Fir at Shawnigan Lake, British Columbia. Canadian Journal of Forest Research 14: 879–884.

Uusvaara, O. 1985. The quality and value of sawn goods from plantation-grown Scots pine. Communicationes Instituti Forestalis Fenniae 130. 53 p.

Valinger, E. 1992a. Effects of thinning and nitrogen fertilization on stem growth and stem form of Pinus sylvestris trees. Scandinavian Journal of Forest Research 7: 219–228.

— 1992b. Effects of wind sway on stem form and crown development of Scots pine (Pinus sylvestris L.). Australian Forestry 55: 15–21.

Vuokila, Y. 1960. On growth and its variations in thinned and unthinned Scots pine stands. Communicationes Instituti Forestalis Fenniae 52(7). 38 p. (In Finnish with English summary)

Total of 37 references