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Effects of Early Thinning Regime and Tree Status on the Radial Growth and Wood Density of Scots Pine

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In this work, we studied the effects of early thinning on the radial growth and wood density over a 12-year post-thinning period in Scots pine (*Pinus sylvestris L.*) trees grown on a site with a rather poor nutrient supply. Ring width, early and late wood width and early wood percentage, mean intra-ring wood density and early- and late wood density were analyzed in 98 sample trees using X-ray microdensitometry. For the analyses, ten different thinning plots with post-thinning stand density varying from 575 to 3400 stems ha^{-1} were grouped into four classes representing heavy thinning, moderate thinning, light thinning and no thinning. We found that the radial growth in the thinned treatments increased significantly compared to that of the unthinned treatment. Despite this, the mean intra-ring wood density did not decrease significantly as a result of heavy thinning, although it was 2% less, on average (with a range of 1–4% in large and small trees), compared to that of the unthinned treatment. In the lightly thinned treatment, the mean intra-ring wood density even increased by 5%, on average (with a range 4–7% in small and large trees), but in the moderately thinned treatment, the level of change was not as clear. The thinning response of trees representing different status in a stand differed significantly and was also affected by the post-thinning stand density. Altogether, observed simultaneous increases in early and late wood widths and late wood density, but a decrease in early wood density indicate that as a result of heavy thinning, especially, un-uniformity of wood density will increase. On the other hand, although heavy thinning increased tree growth by 9–20%, on average, compared to moderate thinning, which corresponds quite well with business-as-usual management, mean wood density decreased only 0–4% depending on tree status in a stand (from large to small trees). Thus, the decrease observed in wood density was less than expected as a result of heavy thinning at an early stage of stand development, which has recently been recommended as one possible management option in Scots pine in Finland.

Keywords thinning response, ring width, early wood, late wood, intra-ring wood density, X-ray densitometry
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1 Introduction

Silvicultural management, such as thinning, affects the growth and wood properties of coniferous trees by accelerating their growth rate, but also through selective removal. Consequently, the wood properties such as wood density, early and late wood and fibre length affect the suitability of harvested trees for pulp and paper production and mechanical wood processing. Wood density significantly impacts on both yield and quality of fibrous and solid wood products, and thus, it is considered to be one of the most important wood quality characteristics (Panshin and De Zeeuw 1980, Megraw 1985, Zobel and van Buijtenen 1989, Zhang 1995, Mörling 2000). Thus, detailed information on the growth and wood density of trees representing different status in the stand would potentially allow the division of the harvested trees dependent on their suitability for the end uses according to their different properties.

In a stand, the dominant and co-dominant trees have usually a higher growth rate and more tapered stems than suppressed or intermediate trees, irrespective of stand density and site fertility (Larson 1963, Kozlowski 1971, Tasissa and Burkhart 1997). Similarly, after a moderate or heavy thinning, and especially if the thinning is done at an early enough stage of stand development, these dominant and co-dominant trees also show higher absolute thinning response compared to suppressed ones because of their improved growing conditions (Ruha and Varmola 1997, Pukkala et al. 1998, Peltola et al. 2002, Mäkinen and Isomäki 2004a,b,c). This means that competition for light tends to modify the growth allocation.

The magnitude of how management, such as thinning, affects the properties of wood in tree stands, depends on thinning intensity and its type, tree species, the status of the tree in a stand and whether juvenile or mature wood is being formed (Olesen 1977, Kärkkäinen 1984, Moschler et al. 1989, Tasissa and Burkhart 1997, Pape 1999a,b, Mörling 2002). In general, the radial growth and the proportion of early wood of conifers has been suggested to increase with increasing growth, whereas wood density, proportion of late wood and fibre length has been suggested to decrease (Hakkila 1966, Persson 1975, Olesen 1977, Zobel and van Buijtenen 1989, Barbour et al. 1994, Lindström 1996, Zhang et al. 1996, Tasissa and Burkhart 1997, Pape 1999a,b, Mäkinen et al. 2002). Increased growth rate has been found to decrease early wood density, especially, but also late wood density (Zhang et al. 1996, Borders et al. 2004). Thus, wood density could be expected to be smaller in the same distance from pith to bark in dominant trees than in suppressed trees at the same age.

Previous studies have, however, found contradictory observations on the effects of thinning on wood density of coniferous trees. For example, in Scots pine (*Pinus sylvestris* L.) and loblolly pine (*Pinus taeda*) little or no changes in wood density were observed despite a significant increase in radial growth due to thinning (Tasissa and Burkhart 1997, Mörling 2000). However, in both Norway spruce (*Picea abies*) and jack pine (*Pinus banksiana*) a slight decrease in wood density was observed after a thinning, mostly in the lower half of the stem (Petty et al. 1990, Barbour et al. 1994, Herman et al. 1998, Pape 1999a,b, Jaakkola et al. 2005). Contradictorily, increased wood density has been observed in some conifers after thinning as a result of prolonged late wood production due to increased soil moisture (Cregg et al. 1988, Zobel and Buijtenen 1989).

In Finland, the business-as-usual forest management recommendations have recently been updated (see Forest Management Recommendations 2006), and now the goals set by individual forest owners place a greater weight on defining how the forest stands will be treated. This means, for example, that in a Scots pine stand in the future, a post-thinning stand density after early thinning at a dominant height of 10–12 m could vary between 700 and 1200 stems ha^{-1} in Southern Finland, whereas in earlier guidelines 1100–1300 stems ha^{-1} was recommended. The reason behind the suggestions for intensified early thinnings is that they are typically delayed in Finland due to the low profitability (Hakkila et al. 1995). So far, little research exists on the effects of intensified management (such as heavy early thinning) on the growth and concurrent changes in wood properties of trees. In the above context, this work studied the effects of an early thinning regime (post-thinning stand density varying from 575 to 3400 stems ha^{-1}) and the tree status in a stand on the radial growth of trees with implications for wood density over a 12-year post-thinning period in a naturally regenerated Scots pine stand.

2 Material and Methods

2.1 Site and Sample Tree Data

The data used in this study was derived from a long-term early thinning experiment established in the summer of 1986 in a naturally regenerated Scots pine stand growing on a site with a rather poor nutrient supply (*Vaccinium* site type) close to the Mekrijärvi Research Station of the University of Joensuu, in North Karelia (62°47´N, 30°58´E, 145 m a.s.l.). Altogether, the experiment employed ten plots (40 m × 30 m), in which the thinning treatments were randomised: one plot was not thinned and nine were thinned from below to densities of 575 to 3400 stems ha^{-1}. The thinning treatments were carried out in the winter of 1986–1987 (Table 1). The experiment was designed to have a gradient of different thinning intensities. Each plot was also surrounded by a 10 m buffer zone, which was treated in the same way as the plot. The mean age at breast height of the stand at the time of early thinning was 22 years, and the initial basal area varied between 20 and 25 m^2 ha^{-1}, with the exception of Plot 3 which had a significantly lower basal area (13.2 m^2 ha^{-1}) even before the thinning treatment (Table 1).

Altogether, 10 trees from each plot (a total of 100 sample trees) were selected to represent different growth rates, and thus also diameter classes, on the plot (three small, four medium-sized and three large trees). These sample trees were felled in the autumns of 1998 and 1999, and cross-sectional discs were taken at a fixed stem height of 1.3 m. From each disc, a wedge of wood 5 cm thick was cut in a north-south direction and oven-dried. These wood samples were further cut into rectangular wood specimens using a twin blade circular saw with an adjustment to reach an angle of 90 degrees to the axis of the tracheid direction (i.e. longitudinal tracheids). The studied samples were 5 mm thick in tangential and vertical direction. The radial length of the samples varied according to the actual distance from pith to bark in each sample. All the samples were carefully air-dried to a moisture content of 12% before measurements with an X-ray microdensitometry. Extractives were not removed, because in earlier, similar studies the wood density contribution of extractives has been estimated to be only about 2–3% (see e.g. Ericson et al. 1973, Mörling 2002).

Table 1. Stand characteristics of plots in the different stand density classes: N = number of stems ha^{-1}, G_{1986} = basal area before the thinning, G_{1987} = basal area after the thinning, D_G = mean diameter at breast height weighted by tree basal area, H_G = mean height weighted by tree basal area, $Age_{1.3}$ = mean age at breast height weighted by tree basal area.

Stand density class	Plot	N, ha^{-1}	G_{1986}, $m^2 ha^{-1}$	G_{1987}, $m^2 ha^{-1}$	D_G, cm	H_G, m	$Age_{1.3}$, yrs
> 3000 ha^{-1}	1	3400	25.1	22.9	10.2	9.8	21.5
	2	3683	22.2	22.2	10.7	9.6	20.2
2000–3000 ha^{-1}	10	2083	23.9	17.3	11.0	10.4	22.7
	5	2383	20.2	16.4	10.0	9.2	22.5
	9	2942	23.2	19.4	10.0	9.6	21.1
1000–2000 ha^{-1}	4	1200	20.6	11.3	11.5	9.9	23.0
	6	1492	20.1	12.7	11.0	9.6	23.2
	8	1800	21.7	14.5	10.9	9.5	22.4
< 1000 ha^{-1}	3	575	13.2	5.1	10.9	9.0	21.5
	7	850	22.4	8.3	11.5	10.2	21.9

2.2 Measurements with X-Ray Microdensitometry

The X-ray microdensitometry used in this research was a commercially available X-ray microscopy (named ITRAX), which was developed by Cox Analytical Systems and located at the University of Joensuu, Faculty of Forest Sciences (see Fig. 1). The instrument operates with a Cu diffraction X-ray tube as a source and uses a specially designed flatbeam collimator and slit-system for confinement of the beam (see Bergsten et al. 2001). The slit-system is 25 µm wide and 22 mm long and the recording device is a diode array with 1024 elements with 25 µm width. The minimum movement step (i.e. pixel size of image) between two measuring points is 25 µm both vertically and horizontally, which is adequate to produce an X-ray image (a digital radiographic image) of a normal year ring sample.

We used standard X-ray intensity for 5 mm thick air dry (12 % moisture content) Scots pine samples (i.e. voltage of 30 kV, current of 25 mA) with an exposure time of 20 ms. Tree rings with a minimum width of 0.3 mm could be expected to be comfortably identified with this step size (i.e. at least 10 measuring points in each ring), but problems with sharp late wood definition may

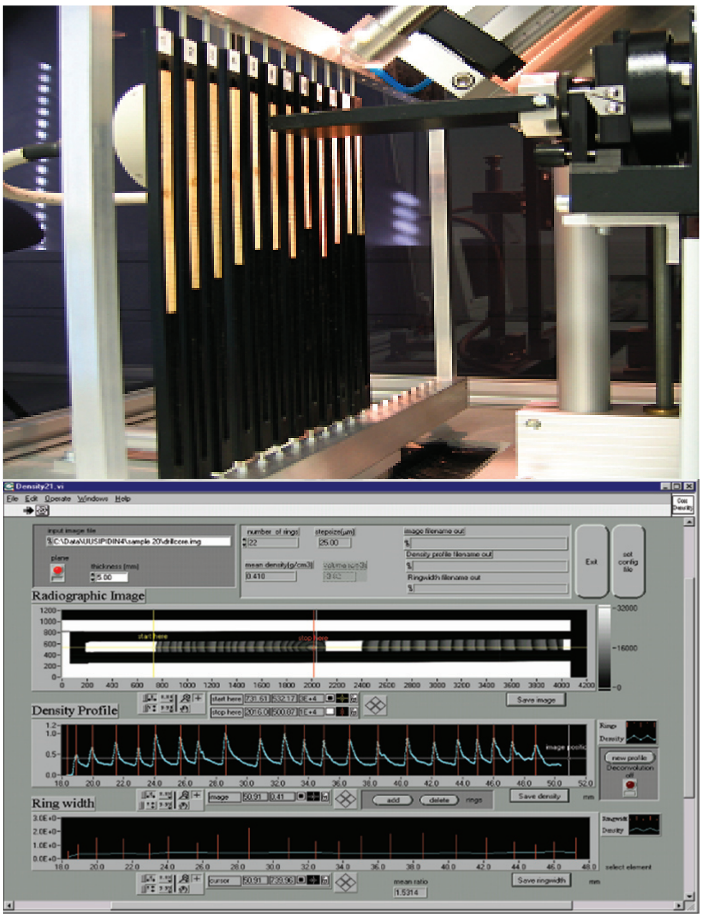

Fig. 1. X-ray microscopy (ITRAX) developed by Cox Analytical Systems (above) and a digital radiographic image and wood density profile for one example sample under analyses in Density software (below).

occur if year ring samples that have grown very slowly are scanned. In the batch scan mode, samples could be placed simultaneously in 20 sample holders (with maximum sample length of about 18 cm). In our holders, the small rectangular wood specimens are located in slits surrounded by a aluminium case (see Fig. 1), which is practical, but also improves the detection precision compared to the original pin type sample holder using adhesive tape to fix samples. We also use a closed cooling system for the X-ray tube to ensure no interruptions in batch scanning (i.e. it keeps a constant tap water pressure).

Density software, as a part of X-ray microscopy, provides a wood density profile based on a digital radiographic image. With the help of this density profile early (EW) and late wood (LW) widths and their percentages, mean intra-ring wood density, minimum (MIND) and maximum wood densities (MAXD) and early- and late wood boundary and mean densities for each annual ring or sample as a whole are calculated by using Excel-macros. When doing this, we define the halfway from minimum to maximum density as a border between the early and late wood. The border between the late wood and early wood of the next year is correspondingly defined as being the point where the sharp decline of the consecutive late wood density measurements ceases and the decrease in density evens out. These definitions used for early and late wood borders were earlier found to work well when ring widths and early and late wood widths were compared in several Scots pine samples based on X-ray density profiles and corresponding microscopic measurements (unpublished data). The borders defined in this way for EW and LW were also supported by a radiographic image analysis of the difference between early and late wood colours.

2.3 Statistical Analyses

To analyse the effects of thinning treatment on the average radial growth of trees (studied here in terms of ring width) with implications for different wood properties (i.e. early and late wood width and percentage, mean intra-ring wood density and early and late wood density), the plots were grouped into 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, corresponding best the business-as-usual management), 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 Plot 1 was very lightly thinned, only with 9% basal area removal of dead and dying trees, and it was regarded as unthinned (see Table 1). In the different density classes 20–30 trees were measured. The mean diameter at breast height (dbh) of the sample trees at the time of early thinning (from sparsest to densest) were 9.1 ± 1.3 cm, 9.5 ± 1.8 cm, 9.0 ± 1.9 cm and 9.3 ± 2.1 cm and the corresponding heights were 9.3 ± 1.1 m, 9.7 ± 0.9 m, 9.8 ± 1.0 m and 9.7 ± 1.1 m.

To analyze the early 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 early thinning. As a result, dbh1 consisted of trees with a diameter of 5.5–7.9 cm (total number of sample trees were 3, 5, 9 and 6 trees from the sparsest stand density class to the densest one), dbh2 trees with a diameter of 8.0–10.4 cm (respectively 13, 15, 15 and 8 trees), and dbh3 trees with a diameter of 10.5–13 cm (respectively 4, 10, 5 and 5 trees). Two trees with a dbh less than 5.5 cm were rejected from the two densest classes because no other similar small trees were found in the other stand density classes. Thus, the analyses were carried out on a total of 98 sample trees.

The data of the annual variables measured using ITRAX represented the period 1984–1998, which was further grouped into 3-year-periods for statistical analyses, i.e. the first 3-year period from 1984–1986 represented the pre-thinning growth and the following 12 years subsequent post-thinning growth period. In the above context, the data analysed separately from pith to bark into two separate directions (i.e. south and north in our case) were averaged for each ring. In a pre-analysis of the data, it was also found that there were not statistically significant differences ($p < 0.05$) in an average pre-thinning radial growth (years 1984–86) between the different stand density classes (also this was the case in same dbh classes in different stand densities). This was expected to provide a good basis for comparing the absolute and relative differences in the growth and wood densities in each diameter class (dbh1–dbh3) between different post-thinning stand density classes and unthinned treatment.

The statistical differences between the thinning treatments were studied with the help of a one-way analysis of variance while the pairwise multiple comparisons were performed using the LSD Posthoc test (SPSS for Windows, Version 13.0, SPSS, Chicago, IL). In all the statistical tests a critical p-value of 0.05 was used. The differences less than that value were defined as statistically significant. Normality and homogeneity of variances of the studied variables were required, but if they were not met, transformations of the studied variables were used for the statistical testing. In the case of ring width and early wood and late wood width, yearly variation in climatic factors was not taken into account, because comparisons were not made between the consequent 3-years periods. Moreover, use of averages of 3-year periods will smooth out most of the annual growth variation. However, when possible differences before the thinning treatments were observed, a 3-year average for a studied variable before the treatment was used as a covariate in an analysis of variance.

The study design was pseudo-replicated, because there were several trees measured from each plot, i.e. trees were not independent observations. In principle, this could have been taken into account by fitting a mixed linear model with a random plot factor for the post-thinning radial growth at breast height using post-thinning stand density and tree diameter as predictors. However, in a previous study by Peltola et al. (2002), which studied the effect of early thinning intensity on the diameter growth distribution along the stem of Scots pines in this same thinning experiment, the random plot factor was found non-significant. This also means that the within-plot correlation could be negligible and, thus, analyses of variance as carried out in this work could be justified.

3 Results

3.1 Radial Growth and Early and Late Wood Width and Early Wood Percentage

3.1.1 Radial Growth

In general, regardless of early thinning intensity or tree status in a stand, a significantly higher radial growth rate was observed in all the thinned Scots pine treatments over the whole 12-year period compared to that of the unthinned treatment (>3000 stems ha^{-1}), in which radial growth decreased as a function of time. However, in the heaviest thinned treatment (post thinning stand density <1000 stems ha^{-1}) the average radial growth for different tree status classes was 87% larger than that of the unthinned one, the corresponding numbers were 50% and 25% in moderately (1000–2000 stems ha^{-1}) and lightly (2000–3000 stems ha^{-1}) thinned treatments, respectively. When other thinning regimes are compared to the moderate thinning, which corresponds quite well the business-as-usual management (i.e. especially in the 2 sparsest plots), we can see that the radial growth is 9–20% higher, on average, in the heavy thinning regime depending on the tree status in a stand (from large to small trees). As a comparison, trees grown under light thinning or without any thinning the radial growth rate decreased by 18–36% compared to moderate thinning regime.

Furthermore, regardless of thinning intensity, the small and medium sized trees grew more in relative terms in response to the thinning than the largest trees did (not seen in the tables and figures, however). But, the largest trees grew more in absolute terms (Table 2). The radial growth (in absolute terms) was also larger the heavier the thinning regardless of tree status in a stand. Over the whole 12-year period, the radial growth was 19, 57 and 92% larger, on average, in the smallest trees (dbh class 1: 5.5–7.9 cm) grown in lightly, moderately and heavily thinned treatments compared to similar sized trees in the unthinned treatment. Corresponding values in medium sized (dbh class 3: 8.0–10.4 cm) and largest trees (dbh class 3: 10.5–13+ cm) were 32, 40 and 102% and 25, 54 and 68% (Fig. 2).

Altogether, the largest relative response in radial growth was observed in the second 3-year period

Table 2. Ring widths (RW) at given diameter classes in the stand density classes over the 3-year measurement periods. Percentage of the change compared with the unthinned plots (>3000 stems ha^{-1}) is given in paranthesis. Significant differences (P<0.05) are marked with *.

	RW (mm)							
	1987–89		1990–92		1993–95		1996–98	
dbh1								
>3000 ha^{-1}	0.76		0.46		0.56		0.49	
2000–3000 ha^{-1}	1.10	(44.6)*	0.95	(108.5)*	0.88	(58.0)*	0.81	(64.2)*
1000–2000 ha^{-1}	1.40	(84.5)*	1.39	(203.0)*	1.20	(114.8)*	1.00	(102.0)*
<1000 ha^{-1}	1.21	(59.9)*	1.78	(288.0)*	1.35	(140.7)*	1.26	(155.0)*
dbh2								
>3000 ha^{-1}	1.11		0.90		0.76		0.81	
2000–3000 ha^{-1}	1.36	(21.8)*	1.19	(32.6)*	1.00	(30.8)*	0.98	(20.0)
1000–2000 ha^{-1}	1.46	(31.3)*	1.36	(50.9)*	1.17	(53.4)*	1.06	(30.9)*
<1000 ha^{-1}	1.50	(35.0)*	2.07	(130.3)*	1.62	(113.3)*	1.72	(111.8)*
dbh3								
>3000 ha^{-1}	1.23		0.94		0.77		0.88	
2000–3000 ha^{-1}	1.60	(30.9)*	1.19	(25.6)	1.09	(41.7)*	1.11	(26.1)*
1000–2000 ha^{-1}	1.73	(40.7)*	1.50	(59.0)*	1.38	(79.2)*	1.22	(38.0)*
<1000 ha^{-1}	1.54	(25.7)*	2.13	(125.2)*	1.58	(105.6)*	1.54	(74.4)*

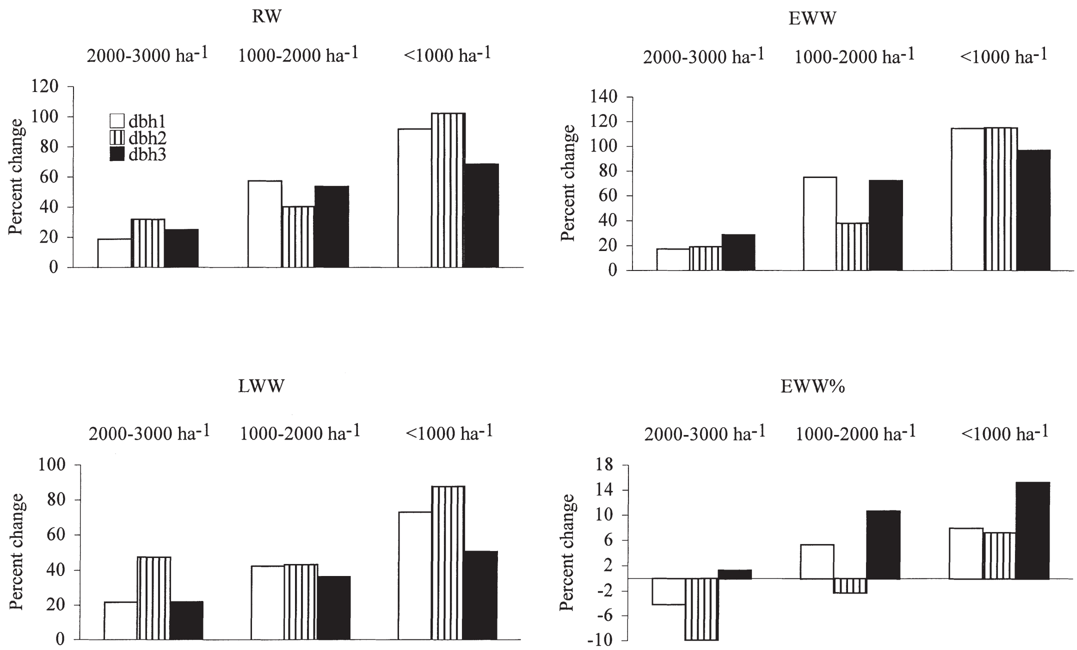

Fig. 2. Ring width (RW), early wood and late wood widths (EWW, LWW) and the percentage of early wood at given diameter classes in the stand density classes over the whole 12-year period after the thinning.

(1990–1992), when it was 125–288% larger, on average, in the largest and smallest sized trees in the heavily thinned treatment compared to the unthinned treatment (see Fig. 2, Table 2). As a comparison, in the lightly (42%) and moderately (79%) thinned treatments the highest relative increases (compared to the unthinned treatment) in the radial growth in the largest trees were observed in the third 3-year period (1993–1995), as was the case also in medium sized trees grown in moderately thinned treatment (53%). As a comparison, in small sized trees grown in the lightly and moderately thinned treatments the relative increases were 109 and 203%, respectively. The highest relative increase in the radial growth (33%) in medium sized trees grown in the lightly thinned treatment was observed already in the second 3-year period (1990–1992). Thus, the maximum response for radial growth was observed earlier the smaller the tree size was at the time of early thinning and the lighter the thinning.

The relative radial growth rate was still, in the final fourth 3-year period (1996–1998) larger on average in all the thinning treatments compared to that of the unthinned one; i.e. in the lightly thinned treatment the increase was between large to small trees 26–64%, and in the moderately thinned and heavily thinned ones 38–102% and 74–155%. These findings for the relative growth response in trees with different tree status in a stand and regardless of thinning treatment differed statistically significantly from that of the unthinned treatment for all the 3-year periods.

3.1.2 *Early and Late Wood Width and Early Wood Percentage*

An increase in radial growth as a result of thinning could also be seen both in early and late wood over the whole 12-year period (Fig. 2). Thus, following the response of radial growth, the width of early wood was also larger the heavier the thinning, in general. In the heavily thinned treatment, the early wood width was 109% larger on average (i.e. average response for different tree status classes) than that of the unthinned one over the 12-year period, when corresponding values in lightly and moderately thinned treatments were, 22 and 62%, respectively. Correspondingly, late wood width increased also on average 30, 41 and 70% in lightly, moderately and heavily thinned treatments, respectively, compared to that of the unthinned one. As a result, average early wood percentage increased in moderately and heavily thinned treatments by 5 and 10% compared to that of the unthinned one, but in the lightly thinned treatment it decreased by 4% over the 12-year period.

Significant differences could also be seen in the effects of thinning treatments on the early and late wood widths and percentages depending on the tree status in a stand over the 12-year period. In small sized trees, early wood width increased from 17% to 114% in the lightly to the heavily thinned treatments compared to that of the unthinned one The respective range in medium sized and large trees was 19–115% and 29–97%. Corresponding figures for the late wood widths were 22–73%, 43–88% and 22–51% from small to large sized trees grown in lightly, moderately and heavily thinned treatments. As a result of these observed changes in early and late wood widths, average early wood percentage increased significantly especially in the heavily thinned treatment regardless of tree size, but the increase was highest in the larger trees (range 7–15%). However, average early wood percentage even decreased in small and medium sized trees grown in lightly thinned treatment (4–10%) and in medium sized trees grown in moderately thinned treatment (2%). Regardless of the 3-year period analyzed, the early wood and late wood widths differed also statistically significantly in trees with different status in a stand and regardless of thinning treatment from that of the unthinned one (unlike the percentage of early wood) (Table 3).

3.2 Wood Density

3.2.1 *Mean Intra-Ring Density*

Despite the significant increase in the radial growth of trees due to the thinning, mean wood density did not statistically significantly decrease over the whole 12-year post-thinning period in any thinning treatment (Fig. 3). The wood density in the heavily thinned treatment was on average 2% less (i.e. average of different tree sizes) than

Table 3. Early wood and late wood widths (EWW, LWW) and the percentage of earlywood at given diameter classes in the stand density classes over the 3-year measurement periods. Percentage of the change compared with the unthinned plots (>3000 stems ha^{-1}) is given in paranthesis. Significant differences ($P<0.05$) are marked with *.

	1987–89		1990–92		1993–95		1996–98	
EWW (mm)								
dbh1								
>3000 ha^{-1}	0.37		0.12		0.17		0.15	
2000–3000 ha^{-1}	0.56	(50.8)*	0.49	(319.1)*	0.44	(151.6)*	0.40	(157.5)*
1000–2000 ha^{-1}	0.78	(109.5)*	0.79	(575.3)*	0.64	(269.4)*	0.52	(241.9)*
<1000 ha^{-1}	0.62	(66.0)*	0.98	(735.2)*	0.73	(323.2)*	0.69	(348.0)*
dbh2								
>3000 ha^{-1}	0.62		0.49		0.39		0.43	
2000–3000 ha^{-1}	0.72	(16.4)	0.63	(28.9)	0.47	(20.3)	0.45	(4.9)
1000–2000 ha^{-1}	0.82	(32.7)*	0.75	(52.5)*	0.63	(60.8)*	0.57	(31.2)*
<1000 ha^{-1}	0.81	(30.8)*	1.21	(146.1)*	0.93	(136.1)*	1.06	(145.0)*
dbh3								
>3000 ha^{-1}	0.63		0.45		0.33		0.38	
2000–3000 ha^{-1}	0.91	(46.1)*	0.64	(40.8)	0.56	(70.5)*	0.55	(45.9)*
1000–2000 ha^{-1}	0.96	(53.2)*	0.87	(91.9)*	0.75	(128.9)*	0.65	(72.6)*
<1000 ha^{-1}	0.87	(38.6)*	1.30	(185.7)*	0.93	(185.7)*	0.90	(137.1)*
LWW (mm)								
dbh1								
>3000 ha^{-1}	0.41		0.34		0.36		0.33	
2000–3000 ha^{-1}	0.53	(29.5)*	0.46	(36.1)*	0.45	(24.3)	0.42	(27.2)*
1000–2000 ha^{-1}	0.61	(48.7)*	0.59	(73.5)*	0.56	(54.5)*	0.47	(44.2)*
<1000 ha^{-1}	0.60	(45.9)*	0.80	(134.4)*	0.61	(68.7)*	0.57	(73.9)*
dbh2								
>3000 ha^{-1}	0.50		0.41		0.37		0.39	
2000–3000 ha^{-1}	0.63	(27.6)*	0.55	(36.2)*	0.52	(41.5)*	0.52	(33.9)*
1000–2000 ha^{-1}	0.64	(29.4)*	0.61	(49.9)*	0.54	(47.0)*	0.51	(31.8)*
<1000 ha^{-1}	0.69	(39.6)*	0.86	(110.5)*	0.69	(88.2)*	0.66	(70.9)*
dbh3								
>3000 ha^{-1}	0.60		0.50		0.42		0.49	
2000–3000 ha^{-1}	0.70	(15.2)	0.55	(8.5)	0.55	(32.2)*	0.57	(15.7)
1000–2000 ha^{-1}	0.77	(26.7)*	0.63	(24.5)*	0.63	(51.6)*	0.56	(15.0)
<1000 ha^{-1}	0.70	(16.3)	0.86	(70.8)*	0.71	(70.8)*	0.68	(39.3)*
EWW (%)								
dbh1								
>3000 ha^{-1}	53.46		44.26		41.22		40.21	
2000–3000 ha^{-1}	48.71	(–8.9)	48.32	(9.2)	46.64	(13.2)	46.53	(15.7)
1000–2000 ha^{-1}	53.85	(0.7)	53.01	(19.8)*	50.00	(21.3)*	49.40	(22.8)*
<1000 ha^{-1}	49.70	(–7.0)	54.72	(23.6)*	53.36	(29.4)*	53.53	(33.1)*
dbh2								
>3000 ha^{-1}	53.63		52.41		48.40		49.03	
2000–3000 ha^{-1}	52.86	(–1.4)	52.74	(0.6)	46.68	(–3.6)	46.25	(–5.7)
1000–2000 ha^{-1}	55.15	(2.8)	53.87	(2.8)	52.13	(7.7)	50.99	(4.0)
<1000 ha^{-1}	53.17	(–0.9)	57.69	(10.1)*	56.34	(16.4)*	58.86	(20.0)*
dbh3								
>3000 ha^{-1}	51.37		47.98		43.06		42.41	
2000–3000 ha^{-1}	55.89	(8.8)	53.67	(11.9)*	49.65	(15.3)*	48.20	(13.7)
1000–2000 ha^{-1}	54.88	(6.8)	56.65	(18.1)*	54.27	(26.0)*	52.92	(24.8)*
<1000 ha^{-1}	54.74	(6.6)	62.23	(29.7)*	58.23	(35.2)*	58.27	(37.4)*

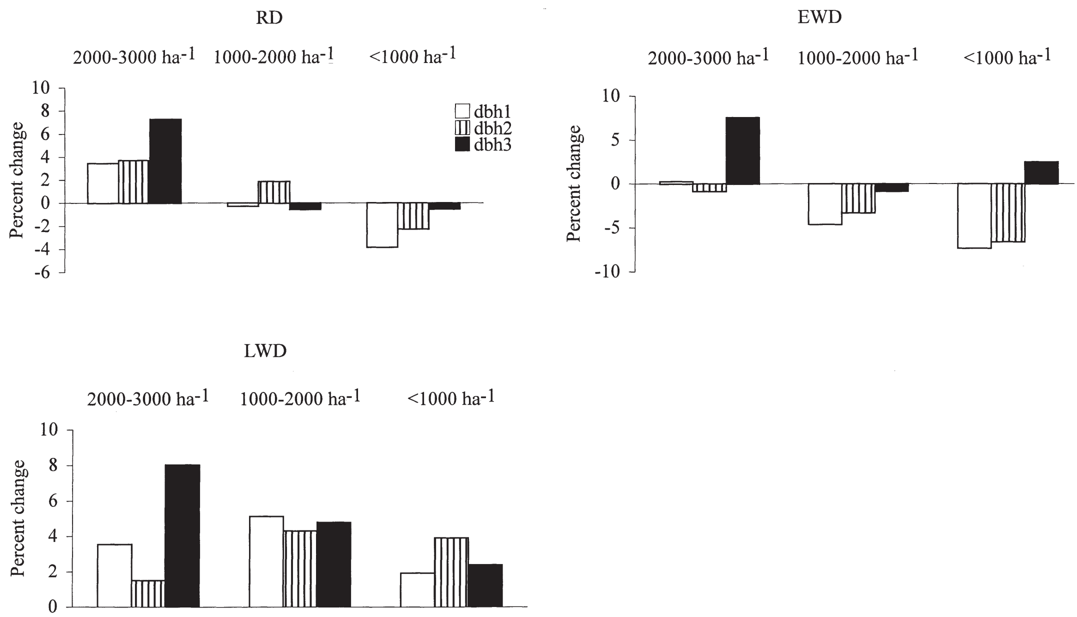

Fig. 3. Mean wood density (RD) and early wood and late wood densities (EWD, LWD) at given diameter classes in the stand density classes over the whole 12-year period after the thinning.

that of the unthinned treatment, for example. Moreover, mean wood density also decreased less in the heavily thinned treatment the better the tree status was in a stand at the time of early thinning, i.e. the decrease ranged between 3.8 and 0.5% in small and large sized trees, respectively. On the contrary, mean wood density increased in the lightly thinned treatment (an average increase of 4.8%). The increase was also larger the better the tree status (range 3.5–7.3%). In the moderately thinned treatment, the change in wood density was not as clear as in the other thinning treatments (average 0.4%, ranged between –0.3 and 1.9% depending on tree status). In general, the mean wood density observed over the 12-year period was smaller, on average, the heavier the thinning or the larger the tree size at the time of early thinning.

When other thinning regimes were compared to the moderate thinning, we found that mean wood density of trees decreased only 0–4% in the heavy thinning depending on the tree status in a stand (from large to small trees), although the radial growth increased due to heavy thinning 9–20%, on average, compared to moderate thinning. Whereas, trees grown under light thinning or without any thinning showed an increase of wood density by 0–8% as a result of decreased radial growth rate by 18–36% compared to moderate thinning regime.

The largest average thinning response on wood density (i.e. average of different tree sizes) was observed during the second 3-year period in the moderately and heavily thinned treatments (Table 4). This was seen clearly in small sized trees, especially, but the timing of the maximum response varied in medium and large sized trees to some degree between the second and third 3-year periods. As a comparison, in the lightly thinned treatment the maximum thinning response in mean wood density was seen in the third 3-year period regardless of tree status in the stand.

3.2.2 *Early and Late Wood Density*

Thinning decreased the average early wood density over the whole 12-year period both in the

Table 4. Mean wood density (RD) at given diameter classes in the stand density classes over the 3-year measurement periods. Percentage of the change compared with the unthinned plots (>3000 stems ha^{-1}) is given in paranthesis. Significant differences (P<0.05) are marked with *.

	RD (g cm^{-3})			
	1987–89	1990–92	1993–95	1996–98
dbh1				
>3000 ha^{-1}	0.46	0.50	0.48	0.48
2000–3000 ha^{-1}	0.49 (6.9)	0.51 (1.4)	0.51 (4.7)	0.48 (0.8)
1000–2000 ha^{-1}	0.46 (0.1)	0.48 (–4.4)	0.49 (2.1)	0.49 (1.2)
<1000 ha^{-1}	0.45 (–2.9)	0.47 (–6.1)	0.47 (–2.6)	0.46 (–3.7)
dbh2				
>3000 ha^{-1}	0.45	0.47	0.47	0.46
2000–3000 ha^{-1}	0.46 (1.9)	0.47 (1.4)	0.49 (6.0)	0.49 (5.5)
1000–2000 ha^{-1}	0.46 (2.3)	0.48 (2.0)	0.47 (0.6)	0.47 (2.7)
<1000 ha^{-1}	0.45 (0.3)	0.46 (–1.7)	0.45 (–2.3)	0.44 (–5.2)
dbh3				
>3000 ha^{-1}	0.43	0.45	0.45	0.45
2000–3000 ha^{-1}	0.46 (7.4)	0.47 (6.3)	0.48 (7.2)	0.48 (8.2)*
1000–2000 ha^{-1}	0.44 (1.5)	0.44 (–1.0)	0.44 (–1.4)	0.44 (–1.1)
<1000 ha^{-1}	0.44 (0.8)	0.44 (–0.9)	0.45 (0.5)	0.43 (–2.4)

moderately (3% compared to the unthinned treatment) and the heavily thinned treatments (4%). However, in the lightly thinned treatment the early wood density even increased (2%). In the heavily thinned treatment, early wood density decreased on average in the small and medium sized trees (7%), whereas in large sized trees it increased 3% compared to that of unthinned treatment (Fig. 3). In the moderately thinned treatment, the early wood density decreased less, regardless of the tree status in a stand, i.e. observed decrease ranged in large and small sized trees between 1–5%. As a comparison, in the lightly thinned treatment the early wood density increased in the large sized trees up to 8% compared to that of the unthinned treatment.

Contrary to the general tendency found in the early wood density, the late wood density increased regardless of the thinning treatment, i.e. on average 3–4% compared to that of the unthinned one over the whole 12-year period. Moreover, in medium and small sized trees the largest increase in late wood density was observed in the moderately thinned treatment (4–5%), whereas in the largest trees the highest increase was observed in the lightly thinned treatment (8%). Early wood and late wood density continued to differ in the final fourth 3-year period (1996–1998) regardless of tree size and thinning treatment compared to that of the unthinned one (Table 5). Thus, the thinning response seemed to last over the whole 12-year period.

4 Discussion and Conclusions

4.1 Differences Observed in Radial Growth and Early and Late Wood Width and Early Wood Percentage

Our work represents one of few studies available regarding the concurrent changes in growth and wood density of Scots pine caused by intensified management, such as heavy thinning in the early stages of stand development, i.e. one possible future option in Scots pine management recommended in Finland. In our work, we used X-ray microdensitometry to analyze how the early thinning regime (post thinning stand density varying from 575 to 3400 stems ha^{-1}) and the tree status in a stand (suppressed to dominant) affects the

Table 5. Early wood and late wood densities (EWD, LWD) at given diameter classes in the stand density classes over the 3-year measurement periods. Percentage of the change compared with the unthinned plots (>3000 stems ha^{-1}) is given in paranthesis. Significant differences (P<0.05) are marked with *.

	1987–89	1990–92	1993–95	1996–98
EWD (g cm^{-3})				
dbh1				
>3000 ha^{-1}	0.32	0.36	0.36	0.35
2000–3000 ha^{-1}	0.34 (5.8)	0.35 (–0.6)	0.36 (–0.6)	0.33 (–3.6)
1000–2000 ha^{-1}	0.31 (–3.3)	0.33 (–7.2)	0.34 (–4.8)	0.34 (–3.1)
<1000 ha^{-1}	0.31 (–3.4)	0.33 (–8.3)*	0.32 (–9.6)*	0.32 (–8.0)
dbh2				
>3000 ha^{-1}	0.32	0.35	0.35	0.33
2000–3000 ha^{-1}	0.32 (–0.9)	0.33 (–4.8)	0.35 (–0.2)	0.34 (2.4)
1000–2000 ha^{-1}	0.31 (–1.9)	0.33 (–4.9)	0.33 (–5.6)	0.33 (–0.8)
<1000 ha^{-1}	0.31 (–3.3)	0.32 (–8.2)	0.32 (–8.5)*	0.31 (–6.4)*
dbh3				
>3000 ha^{-1}	0.30	0.32	0.33	0.33
2000–3000 ha^{-1}	0.32 (8.2)*	0.35 (9.0)*	0.36 (7.0)*	0.35 (6.0)
1000–2000 ha^{-1}	0.30 (1.3)	0.32 (1.1)	0.32 (–3.6)	0.32 (–2.1)
<1000 ha^{-1}	0.31 (5.4)	0.33 (3.2)	0.34 (1.9)	0.32 (–0.6)
LWD (g cm^{-3})				
dbh1				
>3000 ha^{-1}	0.63	0.63	0.59	0.60
2000–3000 ha^{-1}	0.64 (1.2)	0.65 (2.7)	0.64 (7.9)	0.61 (2.4)
1000–2000 ha^{-1}	0.64 (1.0)	0.65 (2.7)	0.65 (10.3)*	0.64 (6.5)
<1000 ha^{-1}	0.59 (–7.6)	0.65 (1.8)	0.64 (8.6)	0.63 (5.0)
dbh2				
>3000 ha^{-1}	0.62	0.61	0.59	0.61
2000–3000 ha^{-1}	0.61 (–1.6)	0.62 (2.5)	0.62 (4.6)	0.61 (0.5)
1000–2000 ha^{-1}	0.64 (3.1)	0.64 (5.9)*	0.62 (5.2)	0.62 (3.1)
<1000 ha^{-1}	0.62 (–0.5)	0.65 (6.8)*	0.63 (6.6)	0.62 (2.7)
dbh3				
>3000 ha^{-1}	0.60	0.58	0.55	0.55
2000–3000 ha^{-1}	0.63 (6.1)	0.62 (5.2)	0.61 (9.6)	0.61 (11.2)*
1000–2000 ha^{-1}	0.61 (1.8)	0.60 (3.5)	0.60 (7.5)	0.58 (6.4)*
<1000 ha^{-1}	0.56 (–6.0)	0.61 (3.8)	0.59 (7.1)	0.57 (4.7)

radial growth (ring width), early and late wood widths and early wood percentages, intra-ring mean density and early and late wood densities in Scots pines grown in a naturally regenerated stand with a relatively low supply of nitrogen. Although our main interest was the average response over the 12-year post-thinning period, we were also interested in the temporal effects of thinning, i.e. when the maximum thinning response was observed and whether the thinning effect lasted over the whole 12-year period.

In our study, the removed basal area was, on average, 62% in the heavily thinned treatment (post-thinning stand density <1000 stems ha^{-1}) and 38 and 21% in the moderately and lightly thinned treatments (post-thinning stand density 1000–2000 and 2000–3000 stems ha^{-1}), respectively. We found that the heavier the early thinning the higher the relative radial growth response, on average, over the 12-year post-thinning period (up to 87%) compared to that of the unthinned treatment. This was also regardless of tree status in a stand (up to 92% in small, 102% in medium and 68% in large sized trees). Moreover, the radial growth did not decline to the level of that of the pre-treatment period in any of the thinned treatments until the end of the 12-year period.

We also observed that the largest trees in a stand had a higher absolute thinning response compared to the suppressed ones, whereas in relative terms the result was opposite. Accordingly, in many previous studies, the dominant and co-dominant trees with the best growing conditions and physiologically efficient large crowns were reported to have a higher growth rate in absolute terms but smaller one compared to suppressed or intermediate trees in relative terms, because they distribute more larger amounts of metabolites to the lower stem (see e.g. Larson 1963, Kozlowski 1973, Tasissa and Burkhart 1997). This has been the case especially if a moderate or heavy thinning has been done at an early enough stage of stand development (see e.g. Moschler et al. 1989, Salminen and Varmola 1990, Ruha and Varmola 1997, Tasissa and Burkhart 1997, Pape 1999a,b, Mäkinen and Isomäki 2004a,b,c). On the other hand, in dominant trees no, or only slightly accelerated radial growth has been observed if delayed or light thinning has been used (e.g. Braastad and Tveite 2001).

In addition to the response of radial growth, we also found that both the early and late wood widths increased, in general, as a response to the thinning, regardless of post-thinning stand density and tree status in a stand. Moreover, the average early wood percentage increased significantly over the whole 12-year period especially with the heavily (up to 10%) and moderately (up to 5%) thinned treatments regardless of the tree size compared to that of the unthinned treatment, but it increased most in the large trees grown in heavily thinned treatment (up to 15%).

Against expectations was that the early wood percentage even decreased especially in small (up to 4%) and medium (up to 10%) sized trees in the lightly thinned treatment. However, this decrease may be explained by the prolonged latewood production due to enhanced growing conditions (e.g. soil moisture conditions). Without any thinning, a moisture deficit may develop within a stand in the late growing season, which can concurrently shorten the period of late wood formation (Cregg et al. 1988, Zobel and Buijtenen 1989). This may be the case also in our unthinned treatment. However, an increase in growth rate has typically been related to a relatively larger increase in width of early wood than that of late wood (see e.g. Larsson 1969, Zhang et al. 1996, Pape 1999a,b, Koga et al. 2002, Jaakkola et al. 2005).

4.2 Differences Observed in Wood Density

Previously, Tasissa and Burkhart (1997) and Pape (1999a,b) suggested that any changes observed in early and late wood percentage in response to thinning could also be expected to be reflected in the intra-ring wood density, as wood density parameters are affected by the early wood and late wood percentage much more than the rate of growth. Moreover, increased growth rate has been previously suggested to decrease wood density, especially in early wood but also concurrently in late wood (Zhang et al. 1996, Borders et al. 2004).

In our work, mean intra-ring wood density tended to decrease slightly over the 12-year post-thinning period as early thinning intensity increased and this happened regardless of tree size. However, statistically significant differences were not found. This was the result even if in the heavily thinned treatment, for example, the intra-ring wood density was on average 2% less than that of the unthinned treatment. The larger decrease observed in mean wood density for small and medium sized trees (range between 4 and 1% in small and large trees) and/or early wood density (average of 4%, range between 7% and 3% in small and large trees) can be related to a significant increase in relative growth rate (and early wood percentage) of these trees in the heavily thinned treatment. Despite this, in small and medium sized trees, mean wood density is generally still higher due to lower growth rate compared to larger trees within the same stand at similar age.

Contrary to the heavily thinned treatment, both mean wood density (average of 5%, range 4–7%) and early wood density (average of 2%, up to 8%) even increased in the lightly thinned treatment, in which the increase was also larger the better the tree status in a stand. Whereas, in the moderately thinned treatment, the change in mean wood density (average change of 0.4%, ranged between –0.3 and 2% depending on tree status) or in early wood density (average change of 3%, ranged between 1–5% depending on tree status) was not as clear as in the other thinning treatments. In our study, the late wood density increased regardless of the thinning treatment, i.e. an average of 3–4% compared to that of the unthinned one over the whole 12-year period. Moreover, in medium and small sized trees the highest increase in late wood density was observed in the moderately thinned treatment (4–5%), whereas in the largest trees the highest increase was observed in the lightly thinned treatment (8%).

As a comparison to our work, Mörling (2002) observed also an average decrease of 4% in mean wood density over a 12-year period in even aged 56-year-old Scots pine trees grown in northern Sweden compared to that of unthinned treatment (but this difference was not statistically significant). In this same experiment radial growth increased by 40 % after the thinning in which 40% of the basal area was removed. On the other hand, the stand density was as low as 1350 stems ha^{-1} already before thinning and the results are, thus, not directly comparable with our findings. Also in Norway spruce and in jack pine only a slight decrease in mean wood density has been observed earlier after a thinning (see Petty et al. 1990, Barbour et al. 1994, Pape 1999b, Jaakkola et al. 2005). In loblolly pine, the wood density hardly changed despite the significant increase in radial growth due to thinning (see e.g. Tasissa and Burkhart 1997). We found the same in the moderately thinned treatment.

In some conifers, even an increase in wood density has also been observed previously following thinning, which has been explained by a possible prolongation in latewood production (Cregg et al. 1988, Zobel and Buijtenen 1989). Similar results were found also in our study in regard to light thinning treatment. Against our findings in Scots pine, mean wood density has also been suggested to decrease as a response to thinning relatively more in dominant trees compared to suppressed ones, e.g. in Norway spruce (Johansson 1993). Compared to these thinning responses discussed above, an increase in the availability of nutrients (due to fertilization) has been observed to decrease the wood density significantly, for example in Norway spruce (Olesen 1976, Zobel et al. 1989, Zhang et al. 1996, Koga et al. 2002, Mörling 2000, Mäkinen et al. 2002). This is thought to be partly related to the increase in proportion of early wood, but also to possible changes in the anatomical structure of the wood, i.e. a larger amount of thin-walled cells.

4.3 Conclusions

A heavy thinning at an early stage of stand development with a post-thinning stand density as low as 700 stems ha^{-1} has been recommended as one possible future management option in Scots pine in Finland (Forest management recommendations, 2006) in order to increase the profitability of early thinning. However, it is unsure if individual trees growing, especially on sites with low fertility, are able to enhance their growth rate enough as a consequence of heavy thinning, i.e. to avoid any considerable decrease in volume increment per hectare (see e.g. Mäkinen and Isomäki 2004a,b). A slight growth reduction on these sites may be acceptable, if it is compensated by larger stem size with a good quality and earlier and larger incomes from thinnings.

In our study, even a heavy early thinning (i.e. post-thinning stand density of 575–850 stems ha^{-1}) did not reduce the mean wood density of trees significantly although it increased the radial growth of trees significantly regardless of tree status in a stand. In our case, the radial growth was due to heavy thinning also 9–20% higher, on average, compared to moderate thinning, which corresponds quite well the business-as-usual management (i.e. especially in the 2 sparsest plots), but still mean wood density of trees decreased only 0–4% depending on tree status in a stand (from large to small trees). The decrease observed in wood density was in this case some degree less than we expected based on enhanced growth rate of trees as a result of heavy thinning at an early stage of stand development. As a comparison, trees grown under light thinning or without any thinning decreased the radial growth rate by 18–36% with a concurrent increase of wood density by 0–8%, compared to moderate thinning regime.

On the other hand, we found that trees representing different status in a stand differed significantly in their growth rate and wood densities regardless of thinning treatment, and the level of this difference tended to be related to the post-thinning stand density. Altogether, simultaneous increase in early and late wood widths, but a decrease in early wood density and an increase in late wood density will explain the statistically non-significant effects of the thinning on mean intra-ring wood density in moderately and heavily thinned treatments. However, our findings indicate that especially as a result of heavy thinning un-uniformity will increase in regard to the intra-ring density with possible implications for strength properties of wood, for example.

Our work represents one of the few studies available in Scots pine, regarding the simultaneous changes observed in growth and wood density as caused by intensified management such as heavy thinning at an early stage of stand development which could be one real option in Scots pine management in the future. This kind of information would be needed as even small differences in certain wood properties such as wood density may be important from the forest industry's point of view (i.e. affecting the processing of the raw material). Moreover, this kind of information on the interactive effects of post-thinning stand density and tree status in a stand on growth and wood density of trees would support the decisions for selective removal in thinning. Furthermore, it allows the division of the harvested trees dependent on their suitability for the end uses according to their different properties.

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