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The effects of pre-commercial thinning and fertilization on characteristics of juvenile clearwood of Scots pine (*Pinus sylvestris* L.)

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Summary

As a result of escalating demands for wood and parts of trees for use as biofuels and energy generation, there is growing interest in increasing forest biomass production. The objective of this study, therefore, was to investigate whether the physical properties and modulus of elasticity (MOE) of Scots pine (*Pinus sylvestris* L.) juvenile clearwood change in response to different silvicultural treatments (pre-commercial thinning and fertilizer application) in 22- to 25-year-old trees. We achieved this by measuring short-term mechanical properties and using X-ray densitometry. The results show that the MOE and latewood density were not affected by any treatment. The earlywood density and the percentages of earlywood and latewood were affected by the treatments. Fertilization increased ring width and the percentage of earlywood but decreased the percentage of latewood. Pre-commercial thinning also increased ring width and the percentage of earlywood, and decreased the percentage of latewood, but did not affect earlywood density. Furthermore, our results suggest that the MOE of wood is not affected by the different treatments as long as the cambial age and ring width are the same and that fertilization should be considered as a factor that increases the site index where intra-ring properties are concerned.

Introduction

As a result of escalating demands for wood, and for various parts of trees for use as biofuels and energy generation, there is growing interest in increasing forest biomass production. In Sweden, this has led to an increase over recent years, of intensive research aimed at enhancing forests and wood production. The possibility of harvesting biomass from so-called young forests, i.e. those with dominant heights below 13 m, is also now being investigated further, as are the effects of more traditional silvicultural management operations such as fertilization and pre-commercial thinning regimes. However, the use of fertilizers in young forests might also raise awareness of problems concerning wood quality in relation to market acceptance. These problems are similar to those described by Cown and van Wyk (2004) who concluded that one of the main impediments for market acceptance of fast grown radiate pine wood is its low quality in respect of its short-term mechanical properties and the poor dimensional stability of its juvenile core wood.

Environmental factors affect the growth and formation of wood properties both in individual trees and in whole stands. For example, competition for light affects the allocation of growth along the stem, and competition for water and/or nutrients affects the overall growth rate (Cannell *et al.*, 1984; Nilsson and Albrektson, 1993; Nilsson and Gemmel, 1993; Nilsson, 1994). Pre-commercial thinning aims to remove trees from the stand to prevent excessive competition between trees while leaving enough trees to achieve high site productivity. Fertilizer is applied in order to create a more optimal level of nutrition for trees. Both these operations can thus have significant effects on tree and wood quality, as well as on biomass production (Satoo and Madgwick, 1982; Thernström, 1982; Salminen and Varmola, 1990; Ruha and Varmola, 1997; Mäkelä and

Vanninen, 1998; Varmola *et al.*, 1998; Karlsson *et al.*, 2002; Mäkinen *et al.*, 2002,;Varmola and Salminen, 2004; Ulvcrona *et al.*, 2007).

The effects of both thinning and fertilization on growth, both for individual Scots pine (*Pinus sylvestris* L.) trees, as well as stands dominated by Scots pine, have been previously studied but mainly in older stands, i.e. >50 years of age. For example, it has been shown that after 5 years, while the initial effect of nitrogen fertilization was to increase total dry matter production per tree and per hectare, no positive effect of thinning was apparent (Valinger, 1993). Combined thinning and fertilization have also been shown to increase the total dry matter production per tree to a greater extent than the additive effects of the treatments when applied singly (Valinger *et al.*, 2000). However, the positive effect of fertilization on radial growth and volume growth was no longer apparent after 8 years (Valinger *et al.*, 2000). When re-evaluated after 12 years, although thinning could still be seen to have had an effect on all the investigated parameters, fertilization only had an observable effect on shoot axes and crown biomass (Valinger *et al.*, 2000). At the level of the stand, volume production decreased with 37 per cent of the control when thinning was the only treatment, with 10 per cent after a combined thinning and fertilization treatment and increased with 20 per cent above the control after fertilization only (Valinger *et al.*, 2000). It can thus be clearly stated that, for Scots pine, both thinning and fertilization can affect development both at the level of the stand and at the individual tree.

An increased growth rate can be expected to result in a lower density within the annual rings of dominant trees than occurs in trees of the same age with their growth suppressed (Peltola *et al.*, 2007). It is therefore vitally important to conduct studies of within-tree properties in order to gain a better understanding of the effects of thinning and fertilization. Because of its industrial importance, several detailed studies have been conducted on the properties of Scots pine wood, as well as on the causes underlying the variation of certain properties within the wood of individual trees (Sauter *et al.*, 1999; Mörling, 2002; Peltola *et al.*, 2007; Ikonen *et al.*, 2008; Vestøl and Høibø, 2010). One important and now widely used method for measuring and analysing intra-ring density is based on scanning with X-rays. Phillips (1960) first started to use the technology to study wood, when he developed a method to use a beam of beta particles to estimate intra-ring density on Douglas fir samples. Several other researchers have further developed the method. The methodology has gained even more widespread use since the 1980s, mainly due to the development of digital output. Some of the early studies, for example, those by Cown and McConchie (1981), Cown and Clement (1983) and Cown and Ball (2001), were particularly important because they formed detailed investigations of intra-ring density, which were applicable to various practical forestry concerns such as the effects of thinning and fertilization. Furthermore, the rapid technical and methodological development of methods for conducting intra-ring studies, as exemplified by Evans *et al.* (1995), have now reached the stage where large quantities of data can be rapidly acquired and the process of intra-ring wood formation subsequently modelled in detail for applications relevant to industrial forestry (Downes *et al.*, 2009). However, these studies mainly concern plantation forestry.

An X-ray densitometry analysis of the eventual effects of thinning and fertilization on the growth rings of Scots pine trees showed that the mean ring width increased by 14 per cent following fertilizer application and by 40 per cent after thinning (Mörling, 2002). However, neither fertilization nor thinning affected ring density (Mörling, 2002). Peltola *et al.* (2007) investigated a total of 98 trees with X-ray densitometry in order to elucidate the effects of different thinning regimes in trials where thinning was performed when stands were 22 years old. Before thinning, stem densities were less than 3700 stems ha$-^1$. No significant decreases in mean wood densities could be found in any of the trial stands, even after the most extreme thinning regimes, i.e. down to <850 stems ha$-^1$ (Peltola *et al.*, 2007). However, none of the above studies has, in any detail, investigated whether any pre-commercial thinning and fertilization treatments affect the juvenile wood of Scots pine.

Studies of the short-term mechanical properties of wood, as they relate to forestry and silvicultural management operations, are being increasingly used both as indicators of possible commercial end-uses of the wood produced and as they relate to other properties of the wood. For example, some recent studies of the short-term mechanical properties of wood include those on the juvenile wood from Radiata pine (Ivkovic´*et al.*, 2008), the effects of thinning in Radiata pine (Raymond *et al.*, 2008), the main and interactive effects of age and clone in Radiata pine (Watt *et al.*, 2010) and studies on round timber of Scots pine (Vestøl and Høibø, 2010). The use of the mechanical properties of wood as a means of comparing the quality of Scots pine clearwood specimens has also been discussed by Verkasalo and Leban (2002).

The current interest in finding ways to increase biomass production means that methods need to be developed that will allow foresters to grow the greatest possible number of stems per hectare, while maintaining stem wood quality. Wood quality can be considered, in general terms, to be a function of a number of wood properties that are correlated with each other. It is now widely accepted that studies of wood should include an account of any potential effects on juvenile wood (Sauter *et al.*, 1999). The formation of juvenile wood has been intensively studied and is related to a number of processes, most of which involve auxin production (Zobel and Sprauge, 1999). In conifers, the transition between juvenile and mature wood differs between species, as well as according to geographic location. For example, in Scots pine in Germany, Sauter *et al.* (1999) studied this transition in detail by X-ray densitometry and concluded that the transition defined by cambial age occurs at between 17 and 21 years of age, depending on the statistical model used.

Further knowledge is required concerning whether, and how, different silvicultural management operations might affect the properties of Scots pine juvenile wood. The objective of this study, therefore, was to investigate whether pre-commercial thinning and fertilizer application affects ring width, the percentage of earlywood, the percentage of latewood, earlywood density, latewood density and the modulus of elasticity (MOE), by examining the short-term mechanical properties of the wood and using X-ray densitometry.

Materials and methods

Stand and site description

The three sites used for this study were established as part of an experiment to evaluate the effects of high stand densities and pre-commercial thinning, combined with a range of different fertilizer application regimes. The experiment, which was designed as a randomized block, included the following treatments: Treatment 1, control—no thinning, no fertilizer; Treatment 2, pre-commercial thinning to 3000 stems ha^{-1} and no fertilizer; Treatment 3, no thinning but fertilizer applied at 100 kg N ha^{-1} every year since 1997 and Treatment 4, pre-commercial thinning to 3000 stems ha^{-1} and fertilizer applied at 100 kg N ha^{-1} once in year 1997. Skog-An + Superba Mikromix were used for the fertilization treatments (Table 1).

The trials were located in northern Sweden at latitudes varying between 63.21°N and 64.17°N (WGS 84 system). The sites of the trial stands were on mineral soils on which young mixed forests were growing from naturally regenerated Scots pine seed trees that had been left after clear-cutting; the sites were subjected to scarification, i.e. they were not planted. The sites were therefore dominated by Scots pine but with some Norway spruce and birch (*Betula* ssp.) included (Table 2). Two of the stands (Renfors and Kulbäcksliden) were established in 1977; Degerön was established in 1980. The stands were therefore 17 or 20 years old when the experiments were established in 1997.

Table 1: Content (per cent) of nutrients in fertilizers used in the field experiment

Nutrient	Superba Mikromix	Skog-AN
N		34.5
NO_3^-		17.25
NH_4^+		17.25
P		
K		
Mg		0.2
S		
Ca		
B	1.2	0.2
Cu	0.3	
Fe	6.8	
Mn	4.1	
Mo	0.1	
Zn	1.0	

The experimental plots measured 900 m^2, each surrounded by a 5 m buffer zone. The soil type at Degerön was sandy loam while it was loamy sand at Kulbäcksliden and Renfors. The altitude varied between 170 and 190 m a.s.l., mean annual precipitation was 700–800 mm (Anonymous, 2010) and the length of the growing season was 120–150 days. On two of the sites, Degerön and Kulbäcksliden, the site index, i.e. the dominant height at 100 years (Hägglund and Lundmark, 1977), was 20 m; the site index at Renfors was 18 m.

Post-treatment stem densities (stems per hectare) varied among the treatments at the different sites as follows: 16 899–44 078 (Treatment 1), 3056–3133 (Treatment 2), 8800–33 000 (Treatment 3) and 2700–3133 (Treatment 4) (Table 2).

In total, 36 Scots pine trees, comprising nine trees from each treatment, i.e. three trees from each sub-plot, were sampled for further analysis. All trees were free from visible signs of disease and other faults at the time of sampling. The sampled trees were selected from the dominant height class to ensure that they were comparable in respect of any silvicultural management treatments of stands that had occurred earlier, as well as during the experimental treatments. Both the pre-commercial thinning treatments and the first thinning in Scots pine dominated stands are generally done according to the schedule 'thinning from below' with removal of wolf trees, and this procedure was also used in the study design by Mäkinen *et al.* (2002).

Sampling was undertaken in autumn 2003 (Treatments 1, 2 and 3) and in spring 2004 (Treatment 4). The following tree variables were measured: DBH (at 1.3 m), tree height (H) and the crown ratio (CR), which is defined as the ratio between living crown and stem length (CR = depth of living crown (decimetre)/total tree height (decimetre)). Mean DBH for the average basal area of trees was calculated according to the instructions for the assessment of plots, as developed by the Swedish University for Agricultural Sciences—Unit for Field-based Forest Research (Karlsson and Ulvcrona, 2010). When examined by site and compared with the respective control plots within sites, the quadratic mean diameters for the average basal area of Scots pine trees were from 75 to 147 per cent of the control (Treatment 2), 21 to 62 per cent (Treatment 3) and 36 to 107 per cent (Treatment 4) (Table 2). The mean CR values were 32, 35.4 and 29 per cent at Degerön, Kulbäcksliden and Renfors, respectively. Further details regarding stand characteristics are presented in Table 2.

Preparation of test specimens

The treatments were grouped into blocks, each block comprising three trees selected from each treatment at each of the three sites, giving nine trees from each management treatment. The four treatments thus give a total of 36 sampled trees. 'Treatment' thus refers to all the trees in each of these grouped blocks, either before or after the different experimental regimes were initiated. All trees were sampled using the following procedure: sample discs from the stem were taken from the same relative height

Table 2: Arithmetic mean DBH (millimetre), quadratic mean DBH average basal area of trees (millimetre), arithmetic mean height (decimetre), basal area (square metres per hectare) and stem density (stems per hectare) in 2002 in the experimental stands

	Species	Treatment	Degerön	Renfors	Kulbäcksliden
Arithmetic mean DBH	Scots pine	1	28.0	27.0	35.5
	Norway spruce	1	30.7	49.5	27.8
	Birch	1	14.8	28.5	19.0
	Total	1	20.1	28.7	26.8
	Scots pine	2	62.4	67.4	82.2
	Total	2	62.2	68.7	74.2
	Scots pine	3	32.5	37.9	32.6
	Norway spruce	3	37.2	71.7	32.9
	Birch	3	16.3	27.7	15.9
	Total	3	23.8	36.4	26.0
	Scots pine	4	74.9	77.5	72.3
	Total	4	71.5	79.0	72.5
Mean DBH average basal area tree	Scots pine	1	54.8	36.7	32.3
	Total	1	42.1	39.1	24.2
	Scots pine	2	60.4	64.4	79.8
	Total	2	59.5	65.6	71.9
	Scots pine	3	79	59.5	39.2
	Total	3	48.7	54.7	29.5
	Scots pine	4	74.3	75.7	66.8
	Total	4	75.5	76.5	67
Arithmetic mean height	Scots pine	1	44.9	53.1	73.3
	Norway spruce	1	46.4	69.2	53.4
	Birch	1	46.0	80.1	58.2
	Total	1	45.8	67.5	61.6
	Scots pine	2	58.4	58.6	70.6
	Total	2	54.6	62.3	66.2
	Scots pine	3	62.8	63.5	85.6
	Norway spruce	3	54.0	74.1	54.8
	Birch	3	56.1	72.3	62.8
	Total	3	57.1	70.0	67.7
	Scots pine	4	63.1	74.8	61.6
	Total	4	62.8	78.3	61.9
Basal area	Scots pine	1	15.6	12.1	13.5
	Norway spruce	1	0.9	2.6	2.1
	Birch	1	7.7	5.6	4.7
	Total	1	24.2	20.3	20.3
	Scots pine	2	8.3	8.9	7.4
	Total	2	8.7	10.6	12.4
	Scots pine	3	25.1	13.3	13.0
	Norway spruce	3	0.9	2.9	5.9
	Birch	3	8.4	4.5	3.7
	Total	3	34.4	20.7	22.6
	Scots pine	4	8.2	11.1	9.0
	Total	4	12.1	14.4	11.0
Stem density	Scots pine	1	6611	11411	16456
	Norway spruce	1	2044	978	822
	Birch	1	8722	4500	26800
	Total	1	17378	16889	44078
	Scots pine	2	2900	2733	1478
	Total	2	3133	3133	3056
	Scots pine	3	5122	4778	10767
	Norway spruce	3	4767	533	533
	Birch	3	8567	3489	21700
	Total	3	18456	8800	33000
	Scots pine	4	1889	2467	2567
	Total	4	2700	3133	3122

at 30 per cent of the tree height. This standard sampling height relative to the height of the sampled tree was used instead of a fixed height at, for instance, 1.3 m because the stands were of different ages and therefore exhibited different stages of development at 1.3 m height. The sampling allowed the use of growth rings that had developed from 1997 to 2002 to be within the definition of juvenile wood, i.e. less than 21 years of cambial age (Sauter *et al.*, 1999). The sampling of trees was based on the fact that before the different treatments were instigated, no significant differences were found among the four treatments in respect of the mean annual ring width (measured with digital callipers) or any other tree characteristics. However, although certain factors were found to differ significantly according to 'site', the benefit of sampling across three separate field trials was felt to better reflect any general effects of treatments in a way that outweighed any drawbacks related to specific site effects, such as, for example, differently aged trees in the younger stand at the Degerön site.

Before the preparation of specimens for the evaluation of their short-term mechanical properties, the sampled discs were placed in a freezer (−20°C) and then dried at 85°C for 48 h, until no further weight decrease could be detected, and the results used to calculate the dry weight biomass.

A 3 mm thick radially orientated transect, from the bark to the pith, was collected from each disc. A final test specimen was collected from each 3 mm transect. This sample contained the six annual rings of wood produced from 1997 to 2002 inclusively and was used to quantify the MOE. This sample was collected in a way that ensured that the wood being tested was produced during the same period as the pre-commercial thinning or fertilizer application, so that we would be able to determine whether the treatments had affected wood formation. These specimens were then conditioned at 66 per cent relative humidity (RH) and 22°C according EN 384 (Anonymous, 1995), before they were subjected to stress and strain measurements.

Analysis of physical properties

All specimens were subjected to X-ray microdensitometry analysis, which included the analyses of those six rings that had been formed during the years 1997–2002. No resin was extracted from the samples before analysis since the aim of the test was to compile density measurements that were comparable among treatments rather than absolute values of density *per se*. Since all specimens contained only sapwood resin, the content can be estimated to be ~3 per cent (Mörling, 2002; Peltola *et al.*, 2007).

Each specimen was mounted on a tray and exposed to X-rays in a Woodtrax instrument (COX Analytical Systems) (Bergsten *et al.*, 2001; Ulvcrona *et al.*, 2006). Metric values, including intra-ring minimum density, earlywood mean density, latewood mean density and maximum density, were determined for each sample from the Woodtrax images using the Windendro software and analysing a 1 mm band located in the middle of the specimen (Bergsten *et al.*, 2001; Ulvcrona *et al.*, 2006). Measurements for the year 1997 are somewhat incomplete because the intra-ring data sets could not be absolutely guaranteed to be complete for all specimens. Consequently, the data for the year 1997 consist of 4, 6, 6 and 8 complete individual intra-ring measurements for Treatments 1, 2, 3 and 4, respectively, while data for the years 1998, 1999, 2000 and 2001 were all complete for all treatments. However, one measurement from Treatment 2 for the year 2002 is missing for the same reason as mentioned above. All other intra-ring measurements within treatments are complete. In order to ensure objectivity, earlywood was defined as having a density of <500 kg m^{-3} and latewood as having a density >500 kg m^{-3}. Cown and Ball (2001) used the latewood definition of 400 kg m^{-3}. However, 500 kg m^{-3} was used here in order that our data might better fit future studies of Scots pine mature wood. The earlywood and latewood percentages were calculated as proportions of the total annual ring width.

Analysis of short-term mechanical properties

Tests of short-term mechanical properties were performed using an INSTRON, a standard testing machine (INSTRON 3366 10 kN) fitted with standard equipment for 3-P bending. The crosshead speed was 0.5 mm min^{-1}, which allowed the test to last for more than 1 min. Each specimen was first tested with 200 N before the actual tests for data acquisition were carried out, in order to induce eventual crack development. This first application of load induced any eventual crack development that might otherwise have influenced calculations of the MOE. Two hundred Newton was also used as the load for the actual test, which ensured that the first application of load did not negatively affect the wood material that was being tested. This procedure allowed the MOE to be calculated for samples of conditioned wood that had been subjected to an initial pre-treatment. In this way, the MOE calculations were comparable among samples. The shear factor was ignored even though it might have had an effect on the actual values of the MOE because the l/h ratio was <10 (Kollman and Coté, 1984). The support length used was the same for all tested specimens at 60 mm, which is shorter than is recommended in EN 384 (Anonymous, 1995). However, because the aim of this study was to evaluate the effects of different silvicultural management operations on comparable specimens, rather than to calculate and present actual MOE values, consideration of the shear factor was unnecessary. The strain was calculated from the measured displacement of the crosshead. Although the above procedure cannot be used to calculate absolute values of the MOE, since measurements were not made directly on the material deformation on specimens, the data are still valid and useful for comparing specimens. Specimens were tested at 22°C and 50 per cent RH. The actual moisture content of each specimen was measured by drying according to EN 384 after testing and this information was then used to adjust the calculated MOE values according to EN 384 (Anonymous, 1995).

The elastic flexural strain, $\varepsilon_{\mathrm{fl}}$, on the bottom surface was calculated as:

$$\varepsilon_{\mathrm{fl}} = 6w_0 h / l^2 \tag{1}$$

where w_0 is the measured deflection and h is the thickness of the specimen.

Flexural stress, σ_{fl}, was calculated as:

$$\sigma_{\mathrm{fl}} = 3Pl / 2h^2 b, \tag{2}$$

where P is the applied load and b is the width.

The MOE was calculated in megaPascals as follows:

$$\mathrm{MOE} = \sigma_{\mathrm{fl}} / \varepsilon_{\mathrm{fl}}. \tag{3}$$

Measurements of the applied load were taken between 100 and 200 N.

Statistical analyses

All statistical calculations were performed in MINITAB (Anonymous, 2007). The data were first tested for normality and heteroscedasticity but the results indicated that no transformations were needed. Differences among the tree and wood variables due to treatments were tested by analysis of variance performed according to the general linear model procedure. Site and treatment were used as model variables, with site as a random variable. Differences were considered significant if Tukey tests returned $P < 0.05$. Regression equations for further describing the relationship between the MOE and annual ring widths within treatments were then calculated according to the standard linear regression method (Zar, 1996). All data were included in calculations except one observation that was considered to be an anomalous outlier since its standard deviation was twice that of the other measurements. Differences between the intercepts and slopes for each treatment were further compared by F tests, where

$$H_0 : \lambda_i = \lambda, \tag{4}$$

$$F = \frac{(\mathrm{SS}_{\mathrm{res}_1 H_0} - \mathrm{SS}_{\mathrm{res}}) / q}{\mathrm{MS}_{\mathrm{res}}}, \tag{5}$$

$$q = \mathrm{DF}\lambda_i - \mathrm{DF}\lambda. \tag{6}$$

Results

The values of the measured tree parameters were as follows for Treatments 1, 2, 3 and 4, respectively, in each case: DBH ranged from 8.5 to 13.6, 8.5 to 11.3, 8 to 13.1 and 8.4 to 12.2 cm; mean heights were 75.6, 67.8, 74.2 and 75.3 dm and mean annual ring widths before establishment were 4, 3.5, 3.8 and 3.2 mm.

The variable site had no significant effect, either in terms of any intra-ring properties or in relation to the MOE of the investigated specimens (Table 3). Treatment had no significant effect with respect to either the MOE or the latewood density (Table 3). The MOE values for specimens containing wood grown between 1997 and 2002 varied between 6111 and 9005, 5721 and 10 766, 5097 and 10 522 and 5813 and 9312 MPa for Treatments 1, 2, 3 and 4, respectively (Table 4). However, treatment did have significant effects with respect to all other investigated intra-ring

Table 3: Analysis of variance tables for the several wood variables investigated

Variable	Source	DF	Seq SS	Adjusted SS	Adjusted MS	*F*	*P*
Ring width	Site	2	0.675	0.6750	0.3375	0.93	0.407
	Treatment	3	3.9253	3.9253	1.3084	3.59	**0.025**
	Error	30	10.9365	10.9365	0.3645		
	Total	35	15.5369				
MOE	Site	2	3603363	3603363	1801681	1.05	0.361
	Treatment	3	12149270	12149270	4049757	2.37	0.09
	Error	30	51299678	51299678	1709989		
	Total	35	67052311				
EW%	Site	2	23.1	23.1	11.55	0.39	0.681
	Treatment	3	422.43	432.43	144.14	4.87	**0.007**
	Error	30	888.79	888.79	29.63		
	Total	35	1344.32				
LW%	Site	2	11.62	11.62	5.81	0.23	0.793
	Treatment	3	478.24	478.24	159.41	6.4	**0.002**
	Error	30	747.01	747.01	24.9		
	Total	35	1236.87				
EW density	Site	2	0.0003959	0.0003959	0.0001979	0.47	0.632
	Treatment	3	0.009546	0.009546	0.003182	7.5	**0.001**
	Error	30	0.0127365	0.0127365	0.0004245		
	Total	35	0.0226784				
LW density	Site	2	0.007219	0.007219	0.003609	0.73	0.489
	Treatment	3	0.006582	0.006582	0.002194	0.45	0.722
	Error	30	0.147642	0.147642	0.004921		
	Total	35	0.161443				

The significant *p*-values are in bold.
DF=degrees of freedom; Seq SS=sum of squares; MS=mean squares.

properties (Table 3). Ring widths of the wood produced during the 6 years 1997–2002 inclusively were higher than the control (Treatment 1) by 14, 28 and 12 per cent in Treatments 2, 3 and 4, respectively (Table 4). Earlywood percentages (EW%) for the same period were higher than the control by 13, 9 and 10 per cent in Treatments 2, 3 and 4, respectively (Table 4). Subsequent latewood percentages (LW%) were lower than the control by 34, 31 and 26 per cent in Treatments 2, 3 and 4, respectively (Table 4). Finally, the earlywood densities were 1 per cent higher than the control in Treatment 2 and 11 and 2 per cent lower than the control in Treatments 3 and 4, respectively (Table 4).

The general effects of fertilization (Treatments 3 and 4) on earlywood properties, i.e. on EW% and earlywood

Table 4: Mean values of investigated wood variables and standard error within brackets

Variable	Treatment 1*	Treatment 2†	Treatment 3‡	Treatment 4§
Ring width	3.118 (0.396)	3.558 (0.629)	4.045 (0.776)	3.489 (0.555)
MOE	7983 (860)	7313 (1593)	6349 (1624)	7239 (974)
EW%	73.14 (5.88)	82.42 (5.42)	79.91 (5.95)	80.12 (3.83)
LW%	26.86 (5.88)	17.58 (5.42)	18.51 (4.03)	19.88 (3.83)
EW density	327.79 (24.59)	331.31 (19.84)	290.1 (12.9)	321.15 (21.84)
LW density	597 (40.9)	560.7 (102.5)	568.7 (44.3)	578.1 (72.2)

* Control: no thinning, no fertilizer.

† Pre-commercial thinning to 3000 stems ha–^{1}, no fertilizer.

‡ No thinning, fertilizer applied at 100 kg N ha–^{1} every year since 1997.

§ Pre-commercial thinning to 3000 stems ha–^{1}, fertilizer applied at 100 kg N ha–^{1} once in year 1997.

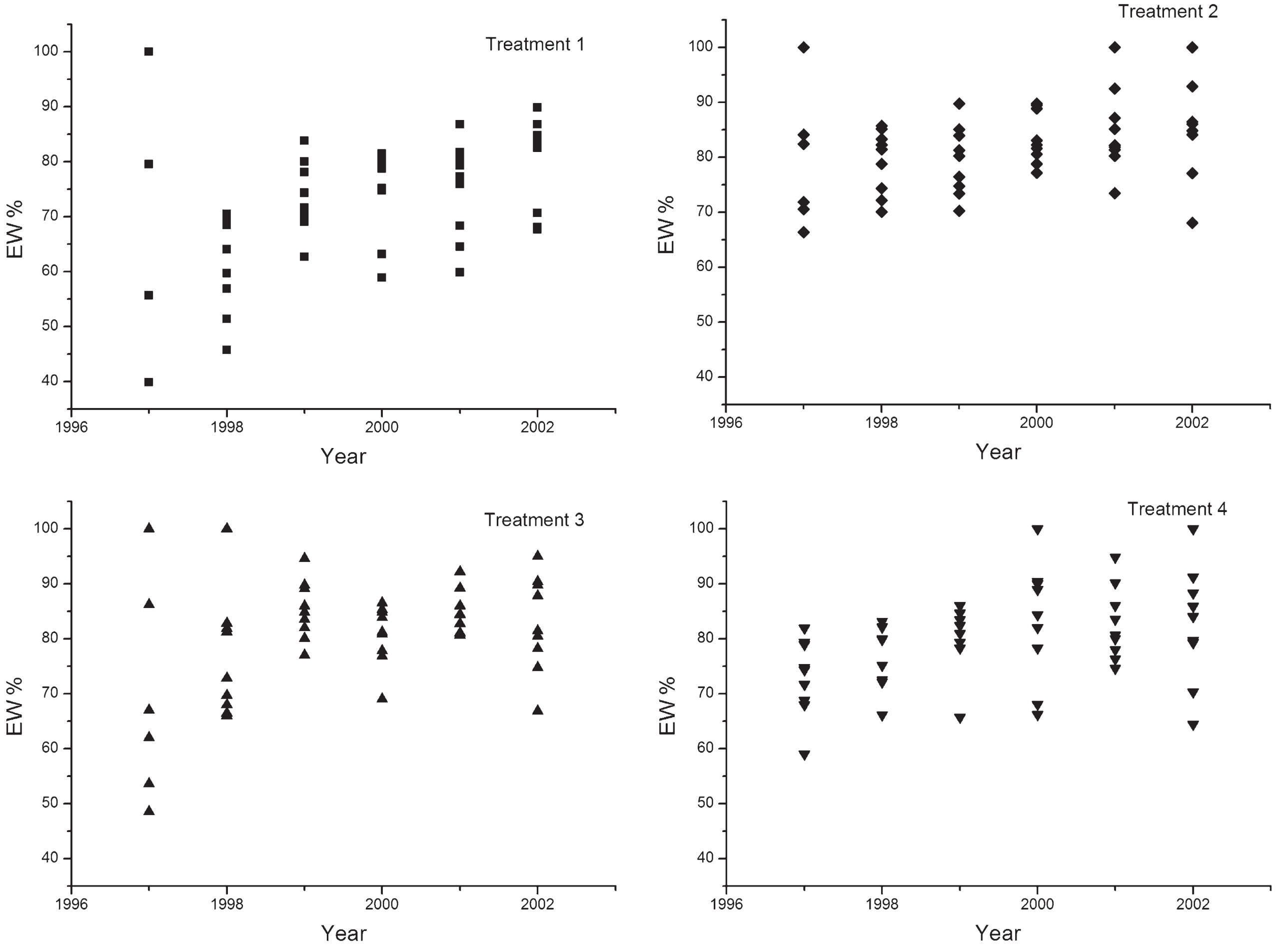

Figure 1. Individual values of EW% measured by X-ray densitometry presented for the actual year of growth. Treatment 1, control—no thinning, no fertilizer; Treatment 2, pre-commercial thinning to 3 000 stems ha–^{1} and no fertilizer; Treatment 3, no thinning, but fertilizer applied at 100 kg N ha–^{1} every year since 1997 and Treatment 4, pre-commercial thinning to 3 000 stems ha–^{1} and fertilizer applied at 100 kg N ha–^{1} 1997.

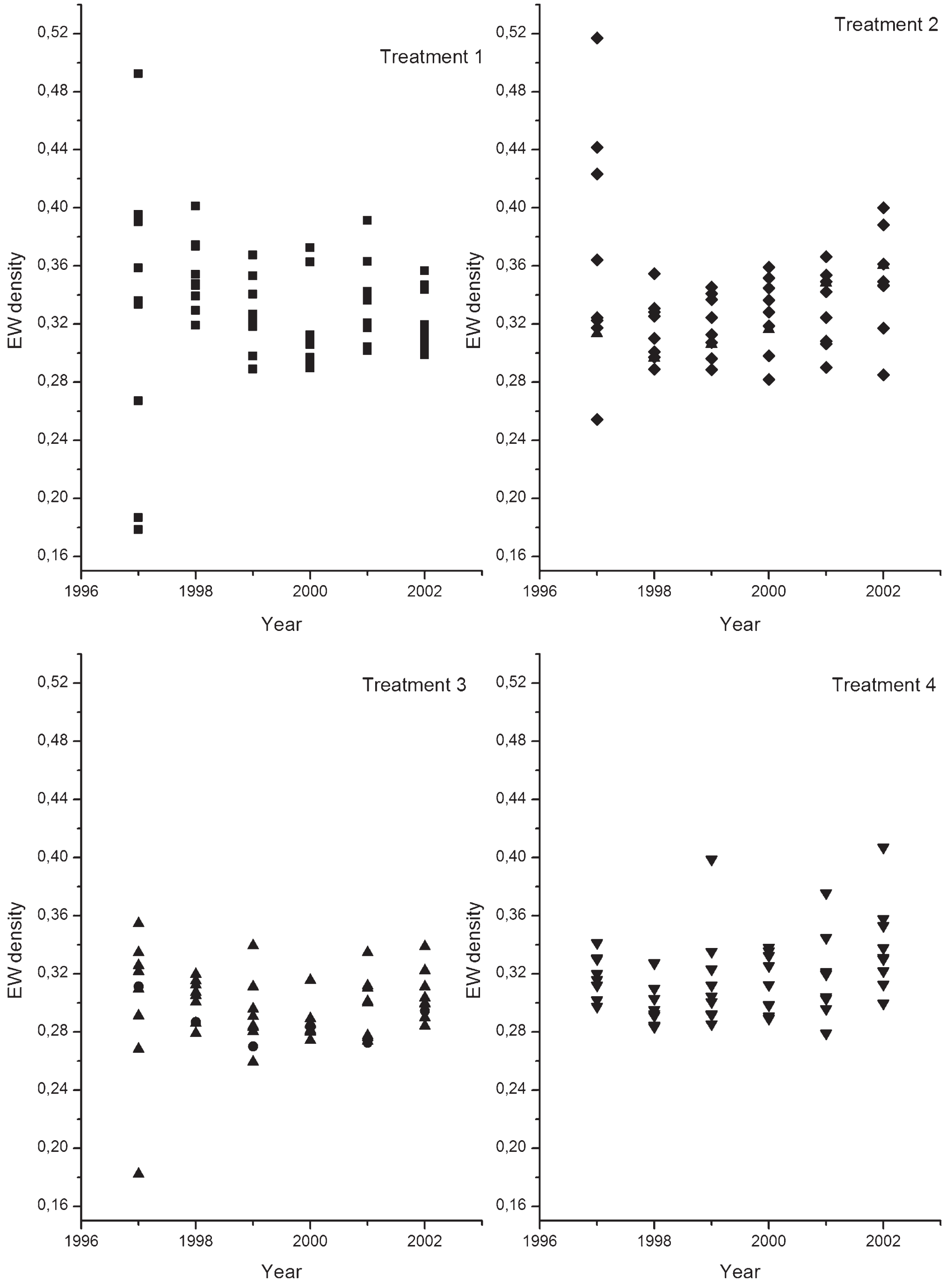

Figure 2. Individual values of earlywood density (<500 kg m^{-1}) measured by X-ray densitometry presented for the actual year of growth. Treatment 1, control—no thinning, no fertilizer; Treatment 2, pre-commercial thinning to 3 000 stems ha^{-1} and no fertilizer; Treatment 3, no thinning, but fertilizer applied at 100 kg N ha^{-1} every year since 1997 and Treatment 4, pre-commercial thinning to 3 000 stems ha^{-1} and fertilizer applied at 100 kg N ha^{-1} 1997.

density, seemed to last for 2–3 years and then to stabilize at the levels then obtained (Figures 1 and 2). When compared within unthinned treatments, fertilization (Treatment 3) seemed first to increase the percentage of earlywood, which then stabilizes, in the already significantly wider rings (Figure 1), at a slightly higher level than was seen in the unfertilized control (Treatment 1) (Figure 1). Within the two pre-commercially thinned treatments (Treatments 2 and 4), fertilization (Treatment 4) did not seem to increase EW% (Figure 1) above that of the unfertilized treatment (Treatment 2). Both showed the general type of development, and they both eventually fell within the same EW% range between 65 and 100 per cent for the wood formed in 2002 (Figure 1). The general effects of pre-commercial thinning (Treatment 2) compared with the control were that EW% reached a higher level immediately after treatment and that even though EW% showed a positive upward trend in the unthinned control specimens, it never quite reached the same level as occurred in the specimens from the pre-commercially thinned treatment (Figure 1).

In general, Treatments 3 and 4, which included fertilization, led to earlywood densities that were slightly lower than the unfertilized treatments (Treatments 1 and 2) (Figure 2). The earlywood density of the two pre-commercially thinned treatments (Treatments 2 and 4) tended to diverge after 2001 and 2002 (Figure 2).

There were no significant effects or clear trends in the latewood densities of any treatment (Figure 3). It seems that the latewood density somewhat decrease over time in Treatments 1, 2 and 4, when it stays relatively stable on a lower level in Treatment 3 (Figure 3).

Although linear relationships were found between the MOE and the annual ring width, which enabled us to calculate regression equations (Figure 4), no significant differences could be found between the slopes of the regression equations for any pair of treatments (Table 5). The relationships between the MOE and the basic wood density was not linear, so it was not possible to fit any regression equations to these data (Figure 5).

Discussion

We used a combination of methods to investigate the effects of various thinning and fertilizer regimes on the intra-ring properties of juvenile clearwood produced during the first 6 years following treatment. Results from our study have shown that the variable site had no significant effect on any of the physical properties of growth rings that we investigated (Table 3), which may indicate that our results are somewhat generally applicable to Scots pine juvenile wood that forms below the green crown border. Other work in Radiata pine has shown that there may be a relatively small effect due to a tree's geographical location on its earlywood and latewood densities (Cown and Ball, 2001). Nevertheless, our results should not be considered as being widely

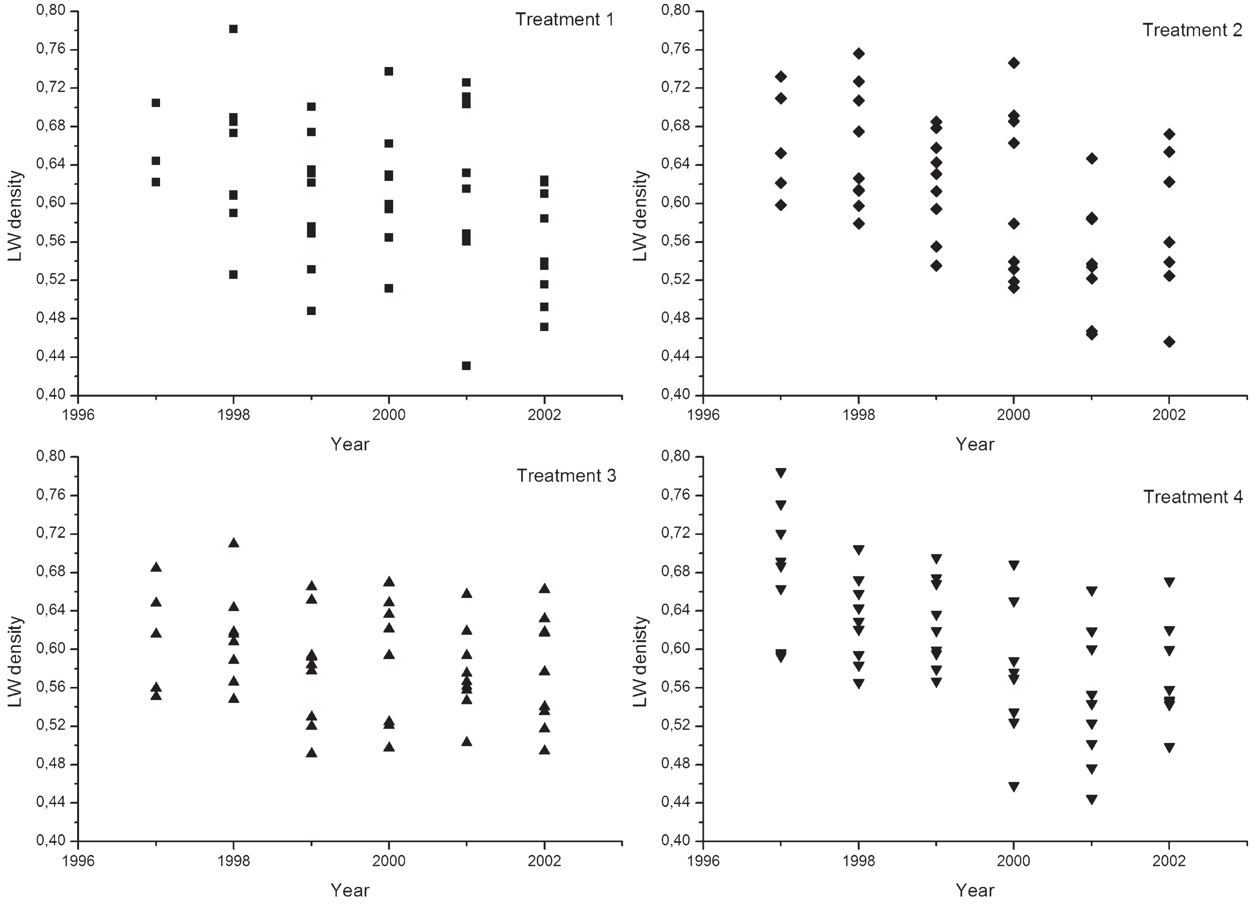

Figure 3. Individual values of latewood density (>500 kg m^{-1}) measured by X-ray densitometry presented for the actual year of growth. Treatment 1, control—no thinning, no fertilizer; Treatment 2, pre-commercial thinning to 3 000 stems ha^{-1} and no fertilizer; Treatment 3, no thinning, but fertilizer applied at 100 kg N ha^{-1} every year since 1997 and Treatment 4, pre-commercial thinning to 3 000 stems ha^{-1} and fertilizer applied at 100 kg N ha^{-1} 1997.

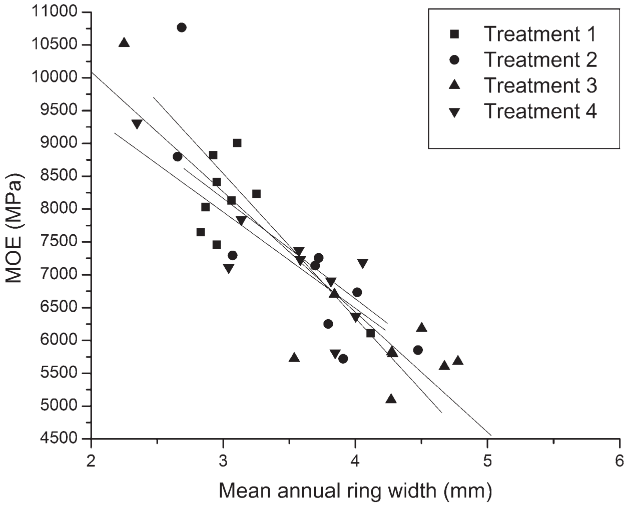

Figure 4. Relationship between the MOE and the mean ring width (millimetres) measured microscopically. Linear regressions for ring width and MOE are shown individually for each treatment. Note: all measurements are included in the figure in order to show the outlier in the data of Treatment 3, which was excluded from the analysis.

Table 5: Regression results for the different treatments

	MOE	*P*
Treatment 1		
Intercept	15 310	0.000
Mean annual ring width (mm)	−1950.1	0.002
N	9	
R^2	73.9	
s	439.1	
Treatment 2		
Intercept	14 700	0.000
Mean annual ring width (mm)	−1978.8	0.001
N	9	
R^2	76.3	
s	775.2	
Treatment 3		
Intercept	14 466	0.000
Mean annual ring width (mm)	−1702.5	0.000
N	8	
R^2	97.2	
s	270.5	
Treatment 4		
Intercept	12 050	0.000
Mean annual ring width (mm)	−1323.7	0.027
N	9	
R^2	45.9	
s	716.6	

applicable to the whole process of wood formation since the main aim of the present study was to investigate in detail only the immediate and principal effects of fertilization and pre-commercial thinning on juvenile wood and are not therefore necessarily relevant to the whole developmental process of wood formation (Zobel and Sprague, 1999).

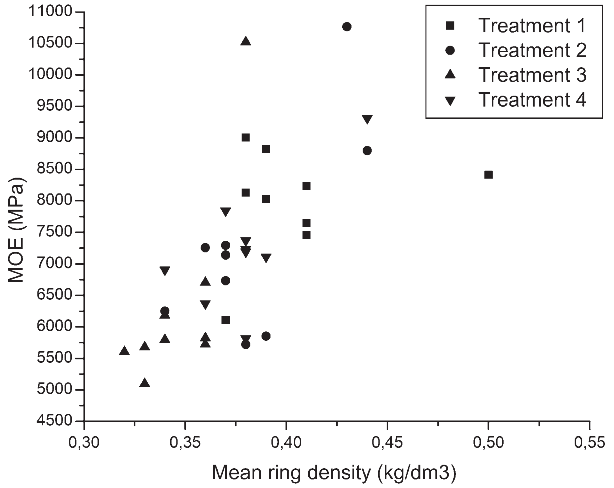

Figure 5. Relationship between the MOE and the mean basic density (kilograms per cubic decimetre) measured microscopically.

Site did have a significant effect on some tree and stand characteristics (Table 2) both in terms of the material sampled for detailed study and in terms of the stands growing at the plots. Numerous recent studies have shown a tree's geographical location, or site, to have a significant effect on both tree and stand development. However, results from these studies are not discussed here as these data are yet to be published.

Treatment had no significant effect on the MOE of the investigated specimen or on the latewood density (Table 3). The MOE results in the present study may reflect the effect of the treatments on microfibril angle more than they reflect any direct effect on the density of the juvenile wood (Table 4). This agrees to some extent with findings reported by, for example, Cown *et al.* (1999). The actual MOE values fall within the general anticipated range previously reported for Scots pine wood (Eriksson *et al*., 2006). Although we did not investigate the microfibril angle in the present study, it might be interesting to do so in future studies since the effects of microfibril angle and densities on MOE clearly need to be further investigated.

Latewood densities in all investigated treatments were similar, with the lowest value in the pre-commercially thinned treatment (Treatment 2) being only 6 per cent lower than the highest values, which occurred in the control (Treatment 1) (Table 4). Few other studies have presented results of detailed intra-ring densities in Scots pine and the effects of different silvicultural treatments on them. One exception is a study by Peltola *et al.* (2007) who also reported that thinning treatments have no significant effects on latewood density. However, a direct comparison between these studies is likely to be unreliable since Peltola *et al.* did not use a fixed definition of latewood. When investigating intensive fertilization of conifers, Mäkinen *et al.* (2002) reported that the absolute wood density not only decreased across the whole annual ring but also did so proportionately more in latewood than in the earlywood of Norway spruce growing in northern latitudes. However, direct comparisons of that study with ours, are again somewhat difficult, not only because of the different tree species but also because they did not use a fixed latewood definition, and because they used both juvenile and mature wood sampled at a height of 1.3 m and pure juvenile wood sampled at a height of 4 m (Mäkinen *et al.*, 2002). Our findings suggest that results from further analyses of whole intra-ring mean densities might be difficult to use if the actual effects of fertilization and pre-commercial thinning are to be investigated.

The silvicultural treatments we investigated did have significant effects on all other intra-ring properties (Table 3). Mean ring widths for the wood produced during the 6 years 1997–2002 were higher than the control (Treatment 1) by 14, 28 and 12 per cent in Treatments 2, 3 and 4, respectively (Table 4). There was little variation between treatments with respect to DBH, which varied from 8.5 to 13.6, 8.5 to 11.3, 8 to 13.1 and 8.4 to 12.2 cm in Treatments 1, 2, 3 and 4, respectively. Altogether, these results indicate that it was the effects of treatments at the intra-ring level that were most apparent.

We found ring width in the fertilized unthinned treatment (Treatment 3) to be 24 per cent higher than the control (Treatment 1), which is in general accordance with results from other studies (Table 4). Mäkinen *et al.* (2002) found that fertilization increased radial growth more than threefold, especially in earlywood width. In another study in Scots pine, although Mörling (2002) did not investigate earlywood and latewood properties in detail, they did find fertilization to have a significant effect on ring width, which increased by between 22 and 24 per cent for the first 8 years after treatment. Similarly, Valinger *et al.* (2000) also found fertilization to have a significant effect on radial DBH growth but only for the first 4 years after treatment. In our study, both treatments that included pre-commercial thinning produced ring widths significantly higher than the control (Table 4). This is in clear accordance with results reported by Peltola *et al.* (2007) who found that larger trees subjected to moderate thinning had growth rings 18 per cent wider than those of an unthinned control. Our results are also in general accordance with those of Valinger (1993), Mörling and Valinger (1999), Valinger *et al.* (2000) and Mörling (2002), although because trees of markedly different sizes and ages were investigated in these studies, as well as different wood tissue types and distinctly different stand conditions and treatments (Table 2), it is hard to draw any detailed conclusions. Nevertheless, since Valinger *et al.* (2000) and Mörling (2002) found that thinning induced a significant response in the radial increment for at least 12 years, the effects of stand densities should be the subject of further study when investigating intra-ring properties because the effect of thinning seems to be more long-lasting than that of fertilization.

In our study, EW% were higher than the control by 13, 9 and 10 per cent in Treatments 2, 3 and 4, respectively (Table 4), and latewood percentages (LW%) were lower than the control by 34, 31 and 26 per cent in Treatments 2, 3 and 4, respectively (Table 4). Peltola *et al.* (2007) found that earlywood increased by 5 to 10 per cent in thinned stands compared with unthinned stands, and these results correspond well with those of similar treatments used in the present study mentioned above in which pre-commercial thinning (Treatment 2) and pre-commercial thinning together with fertilization (Treatment 4) resulted in increases of 13 and 10 per cent, respectively. As discussed above, Mäkinen *et al.* (2002) also reported a similar tendency in fertilized Norway spruce. The findings of Valinger *et al.* (2000) and Mörling (2002) also point in this direction. However, again, because of the different methods used in these various studies, it is hard to draw detailed conclusions from any comparisons. The weak trend observed in our study does, however, seem to suggest that fertilization (Treatments 3 and 4) causes EW% to reach a stable level 1 or 2 years earlier than it does in the absence of fertilization (Treatments 1 and 2) (Figure 1), but this apparent trend needs to be investigated further.

The earlywood densities were 1 per cent higher in Treatment 2 than the control (Treatment 1) (Table 4) and 11 and 2 per cent lower than control in Treatments 3 and 4, respectively (Table 4). These findings correspond well with the effects that moderate thinning in Scots pine has on earlywood densities in Finland (Peltola *et al.*, 2007). This decrease due to fertilization is also over 20 per cent lower than the decrease of ring density in Norway spruce reported by Mäkinen *et al.* (2002). Furthermore, since the treatments had no effect on latewood densities, it seems that the fertilization treatments used in the present study did not lower wood density to the same degree as reported by Mäkinen *et al.* (2002). Mörling (2002) also reports the same tendency for ring densities in relation to fertilization in older Scots pine trees. While our findings that the fertilization effect seems to last for only 2–3 years do not compare with other studies in Scots pine, they do not contradict some other studies, e.g. Mörling (2002), who concluded that fertilization has a shorter-term effect than thinning. However, pre-commercial thinning did not have any effect on earlywood density, which is somewhat contradictory to the findings of Mörling (2002) who reported a significantly lower density due to thinning in Scots pine, although Mörling's (2002) study was of older trees that had grown in a markedly different environment. This difference in response to treatment is interesting and needs further investigation, as does the suggestion that earlywood density in trees from pre-commercially thinned stands (Treatments 2 and 4) and non-thinned stands (Treatments 1 and 3) might diverge (Figure 1).

Cown and McConchie (1981) reported a much larger response in Radiata pine wood if thinning and fertilization were used together than if either were used alone. Valinger *et al.* (2000) and Mörling (2002) also report the same combination effect, but interestingly, this effect did not seem to be present in the present study (Tables 3 and 4; Figures 1 and 2). When comparing pre-commercial thinning (Treatment 2) with pre-commercial thinning and fertilization (Treatment 4), there seems to be little difference in the responses to treatments or in any trend relating to ring width, EW%, LW% or densities in different wood tissues (Table 4; Figures 1 and 2). This absence of response to fertilization might be due to the fact that fertilization was done in close relation to the pre-commercial thinning, which may have led to the remaining trees having difficulty in utilizing the available nutrients. The effects of fertilization in combination with pre-commercial thinning and thinning operations within all diameter classes are therefore in need of further investigation.

No differences could be found in the relationships between treatments and the MOE (Table 3), even when we compared the slopes of linear regression lines describing the relationships between MOE and ring width (Table 5). It is important to note that the accuracy of the linear regressions was low due to the relatively small sample size. However, there even appears to be no difference in the MOE of woods with similar ring widths formed in response to the different treatments. The MOE is an emergent property of the underlying structure of the specimen; it provides information on how the material behaves in its present state under a moderate external load. It is therefore important to relate actual MOE values to some aspect of the wood's structure when using MOE to describe this structure. Annual ring width correlated well with the MOE values we obtained (Figure 4) and provided a better description of the wood. We have chosen to present the results pertaining to the MOE in relation to annual ring width, instead of basic density, because the relationship between the MOE and basic density was generally very weak (Figure 5). The results indicate that there were no major differences in the MOE of woods with the same ring widths, even though they had developed under different silvicultural management systems. This indicates that fertilizer application, pre-commercial thinning or the absence of these treatments does not affect the MOE of juvenile wood, as long as ring widths are the same. This means that as far as intra-ring properties are concerned, fertilization should be considered as a treatment that mainly affects the site index.

The present study investigated intra-ring and short-term mechanical properties of clearly defined juvenile wood of Scots pine and related the effects of fertilization and pre-commercial thinning on those properties. This work, therefore, complements earlier studies mentioned above and those of Satoo and Madgwick (1982), Thernström (1982), Salminen and Varmola (1990), Ruha and Varmola (1997), Mäkelä and Vanninen (1998) and Ulvcrona *et al.* (2007). Even more detailed analyses are planned for the future in order to provide more information on wood formation, forest production and wood properties in relation to industrially relevant silvicultural management operations, with the aim of making future forest industries processes the basis on which the production of forest raw materials are evaluated.

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Conflict of Interest Statement

None declared.

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