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Original article

Evaluation of annual ring width and ring density development following fertilisation and thinning of Scots pine

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Abstract – Effects of nitrogen fertilisation and thinning, 40% basal area removal, on annual ring width and ring density were studied in a 2×2 factorial field experiment in northern Sweden, in an even aged 56-year-old Scots pine stand twelve years after treatment. Each treatment was replicated six times. From four stem heights, wood specimens were measured using direct scanning X-ray microdensitometry. For the whole period, mean ring width increased by 14% following fertilisation and by 40% after thinning. Neither fertilisation (< 1%) nor thinning (–4%) significantly ($p > 0.05$) changed ring density during the twelve-year period. Based on four-year mean values at 1.3 m, ring width increased in all cases, except for fertilisation in the last four-year period. The only significant effect on wood density was a 5% decrease following thinning during the second four-year period. Linear regression showed negative correlation between ring density and ring width and no additional effects of treatments per se.

growth / *Pinus sylvestris* / wood density / X-ray densitometry

Résumé – Évaluation de la largeur et de la densité des cernes après fertilisation et éclaircie dans un peuplement de pin sylvestre. Les effets de la fertilisation et de l'éclaircie sur la largeur et sur la densité des cernes ont été étudiés dans un peuplement expérimental du nord de la Suède, 12 ans après traitement, dans un peuplement équienne de pins sylvestres, âgé de 56 ans. Chaque traitement était répété six fois. Des échantillons de bois représentant deux rayons opposés ont été prélevés à quatre hauteurs et analysés par microdensitométrie scanning direct. Au cours des douze années après traitement, la largeur moyenne du cerne a augmenté de 14 % après fertilisation et de 40 % après éclaircie. Ni la fertilisation (< 1 %), ni l'éclaircie (–4 %) n'ont eu d'effect significatif ($p > 0,05$ %) sur la densité des cernes durant la période de douze ans. La largeur du cerne à 1,30 m, basée sur des moyennes de quatre ans, a augmenté dans tous les cas, sauf lors de la fertilisation pour la période des quatre dernières années. Le seul effet significatif sur la densité de bois était une diminution de 5 % suivant le traitement d'éclaircie durant la deuxième période de quatre ans. Une régression linéaire a démontré une corrélation négative entre la densité des cernes et la largeur du cerne et pas d'effet additionnel du traitement lui-même.

accroissement radial / pin sylvestre / densité de bois / microdensitométrie

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1. INTRODUCTION

A major objective of silviculture is to produce valuable timber. To promote growth of individual trees, fertilisation and thinning are commonly used. These treatments may also affect the properties of the wood produced, including general tree features (abundance and distribution of knots, stem straightness, compression wood, juvenile wood, etc.) and clear wood properties (wood density, tracheid dimension, microfibril angle), see Briggs and Smith [4]. Wood density is considered to be the single most important clear wood property because of its correlation to important end-use characters in solid wood, pulp, paper, and fuel wood, and in addition it is easy to measure [19, 31]. In this paper the term wood density refers to basic density, defined as oven dry weight divided by green volume [19].

Among conifers, increased radial growth as an effect of fertilisation is generally associated with a decrease in wood density ([32], pp. 224–227). Decreased wood density following fertilisation has been reported [5, 12, 17, 20, 30]. The most pronounced wood density decrease occurs in the lower part of the bole [5,12].

Literature concerning thinning effects on wood density in conifers is inconsistent ([19] and [32], pp. 224–227). Paul [25] report both increased and decreased wood density responses in different stands of *Pinus taeda* L. following thinning. Ericson [8] found no differences in wood density between actively thinned and naturally thinned stands in *Pinus sylvestris* L. but a 7% decrease in *Picea abies* (L.) Karst. Several other studies report unchanged wood density following thinning [20] (*Pseudotsuga menziesii* (Mirb.) Franco), [22] (*Pinus taeda*), [27] (*Pinus taeda*)). In a study of *Pseudotsuga menziesii*, Jozsa and Brix [12] report a slightly increased wood density following thinning in the lower part of the bole, whereas thinning tended to decrease wood density in the upper part of the bole. This is contrasted by the decreased wood density as a response to thinning reported by Barbour et al. [2] in *Pinus banksiana* Lamb. and by Pape [24] in *Picea abies*.

In the fertilisation and thinning experiment subject to investigation in the present study, fertilisation and thinning effects on single tree growth and distribution of biomass and volume after twelve years have been investigated by Valinger et al. [29]. Fertilisation increased stem volume but did not affect stem biomass. Thinning was found to increase both stem biomass and volume. Results also showed that growth of stem volume was increased by fertilisation the first eight years, whereas thinning increased stem growth throughout the whole twelve year period. The result of Valinger et al. [29] indicated a decreased wood density following fertilisation whereas the effect of thinning on wood density was not established.

The aim of the present study was to (i) evaluate effects of fertilisation and thinning on ring width and ring density and (ii) to establish the relation ring width – ring density and test if there were additional effects of fertilisation and thinning on ring density. Radial and vertical differences were characterised on four stem heights. Effects were analysed on basis of twelve-year mean values, four-year period mean values, and as individual annual ring values.

2. MATERIALS AND METHODS

2.1. Site

The study was performed in an even-aged Scots pine stand established in 1939 at Vindeln (64° 14’ N, 19° 46’ E, 200 m a.s.l.) in northern Sweden [28]. The stand was regenerated by both direct seeding and natural regeneration. Seed trees were felled in 1956, and the stand was pre-commercially thinned in 1972. At the start of the experiment in 1983, top height was 13.2 m, and the corresponding age at breast height (1.3 m) was 34 years. This is indicative of a site index of $SI_{100} = 23$ (top height 23 m in even-aged stands at 100 years of total age), according to Hägglund and Lundmark [10]. Soil type was a mesic sandy silty moraine with ground vegetation dominated by *Vaccinium vitis idaéa* L. and *Vaccinium myrtillus* L. Stand density was 1350 stems ha^{-1}, mean arithmetic diameter at 1.3 m was 13.7 cm, basal area was 20 m^2 ha^{-1}, and total stem volume, calculated according to Näslund [23], was 116 m^3 ha^{-1}.

2.2. Experimental design

The experiment was designed as a 2 × 2 factorial fertilisation and thinning experiment with 12 replications (blocks). The treatments were control (T_0F_0), thinning (40% basal area removal; T_1F_0), fertilisation (150 kg N ha^{-1}; T_0F_1), and thinning × fertilisation (T_1F_1). An autumn thinning in 1983 removed 46% of the stems from the full range of diameter classes. Urea was applied by hand in the spring of 1984 before growth commenced. The experiment was laid out using a rectangular grid of adjacent plots with a gross plot area of 0.09 ha (30 × 30 m) and a net plot area of 0.04 ha (20 × 20 m), giving a 5 m treated buffer zone around each net plot. Plots were ranked by basal area and sorted into 12 blocks of 4 with basal area differences within blocks of less than 1 m^2 ha^{-1}. The four treatments were randomised within the blocks, giving 12 replications of each treatment.

2.3. Sampling

Snow and wind had in 1995 caused damage to six of the blocks. In the remaining six undamaged blocks, diameter on bark at breast height, tree, and crown heights was measured on all trees. On each plot basal area and mean tree basal area was determined. From each plot a number of undamaged trees with basal area as close as possible to the mean tree basal area of the plot were selected for felling and study. In two of the six blocks, six undamaged trees were selected from each plot. From these 48 trees, stem discs, about 2 cm thick, at 1.3 m were selected for density measurement. In the remaining four blocks, two trees per plot were selected. From these 32 trees, stem discs were taken from four levels; level 1 = 1%, level 2 = 1.3 m, level 3 = 35%, and level 4 = 65% of tree height. Consequently, level 2 was represented at six of the blocks whereas levels 1, 3, and 4 were represented at four of the blocks. Plot mean values of sample tree data per treatment are shown in *table I*.

Out of each stem disc, wood specimens representing two opposing radii in north-south direction were sawed to 1 mm thickness, using a twin-blade circular saw [15]. The specimens were measured with a direct scanning X-ray microdensitometer with automatic collimator alignment [26]. The geometrical resolution, defined by the collimator slot, was 0.02 × 1 mm, i.e. 50 measurements per mm. Microdensitometric data obtained was processed in a software program to determine annual ring characteristics [14]. For each annual ring, year of ring formation, ring position (mm from bark), ring width (mm), and average ring density (kg m^{-3}) were calculated. Density values from the X-ray measurements were calibrated by gravimetric measurements. From the X-ray wood specimens 40 specimens of 0.1 cm^3 (32.5 × 3.1 × 1 mm) were punched for calibration measurements. Samples were taken systematically with respect to plot and height so that equal representation for each plot and each height was ascertained. Specimens were kiln dried for 16 h in 103 °C until no further loss in weight was observed. Moisture content before drying was 6%. The X-ray density values were then calibrated to represent basic density values according to the mean weight of the dried specimens. No systematic deviation with height, treatment or block was noticed.

2.4. Calculation and statistics

For each growth ring, mean values of ring width and ring density from two opposing radii were calculated. Treatment effects in ring width and ring density were calculated as mean values for the whole 12-year period, as well as for three four-year periods: period 1 = 1984–1987, period 2 = 1988–1991, and period 3 = 1992–1995. To establish possible differences before treatment, mean values for the period 1980–1983 were calculated. Mean ring width was calculated as total ring width for the period divided by number of years. In order to correctly calculate mean ring density for the different time periods, ring density was weighted with ring width for each year;

mean ring density = Σ (ring density × ring width)/ Σ ring width.

Table I. Plot mean values per treatment 1995. F_0T_0 = no fertilisation, no thinning, F_1T_0 = fertilisation, no thinning, F_0T_1 = no fertilisation, thinning, F_1T_1 = fertilisation and thinning. Standard error between plot means are indicated in parentheses.

Treatment	*n*	Height (m)	Crown length (m)	Crown ratio	Diameter under bark (cm)*	Age *
F_0T_0	6	14.8 (0.61)	7.1 (0.33)	0.48 (0.020)	15.8 (0.31)	41.3 (1.1)
F_1T_0	6	15.6 (0.37)	7.5 (0.19)	0.48 (0.016)	16.1 (0.33)	42.6 (1.3)
F_0T_1	6	14.6 (0.37)	7.8 (0.24)	0.54 (0.024)	17.0 (0.41)	42.1 (1.5)
F_1T_1	6	15.2 (0.16)	8.1 (0.23)	0.53 (0.016)	18.2 (0.28)	41.6 (0.8)

* values at 1.3 m.

Treatment effects for level 1–4 for the 12-year period based on plot means for four blocks were calculated by an analysis of variance model:

$$\begin{aligned} y_{ikhj} = {} & \mu + \alpha_i^{(F)} + \alpha_k^{(T)} + \alpha_{ik}^{(FT)} + \alpha_h^{(\text{Height})} + \alpha_{ih}^{(F\,\text{Height})} + \alpha_{kh}^{(T\,\text{Height})} \\ & + \alpha_{ikh}^{(FT\,\text{Height})} + b_j^{(\text{Block})} + c_{ij}^{(F\,\text{Block})} + d_{kj}^{(T\,\text{Block})} + f_{hj}^{(\text{Height Block})} \\ & + g_{ikj}^{(F\,T\,\text{Block})} + m_{ihj}^{(F\,\text{Height Block})} + n_{khj}^{(T\,\text{Height Block})} + e_{ikhj} \qquad (1) \end{aligned}$$

For each four-year period treatment effects at 1.3 m based on plot means from six blocks were calculated as:

$$\begin{aligned} y_{ikj} = {} & \mu + \alpha_i^{(F)} + \alpha_k^{(T)} + \alpha_{ik}^{(FT)} + b_j^{(\text{Block})} + c_{ij}^{(F\,\text{Block})} \\ & + d_{kj}^{(T\,\text{Block})} + e_{ijk} \qquad (2) \end{aligned}$$

The models are mixed statistical models where block is a random factor:

μ: overall mean; α: fixed effect; b: random effects; i and k: level of F (0 = no fertilisation, 1 = fertilisation) and T (0 = no thinning, 1 = thinning) respectively; h: height (1 = 1% of tree height, 2 = 1.3 m, 3 = 35% of tree height, 4 = 65% of tree height); j: number of block.

All fixed effects are zero over all indices, and all random effects are

$$b_j \in \text{NID}(0,\sigma_b^2),\ b_{ij} \in \text{NID}(0,\sigma_b^2),\ b_{kj} \in \text{NID}(0,\sigma_b^2),$$
$$b_{hj} \in \text{NID}(0,\sigma_b^2),\ b_{ikj} \in \text{NID}(0,\sigma_b^2),\ b_{ihj} \in \text{NID}(0,\sigma_b^2),$$
$$b_{khj} \in \text{NID}(0,\sigma_b^2)$$
$$e_{ikhj} \in \text{NID}(0,\sigma^2)$$

and mutually independent.

In model (1) the interaction effect $F \times T \times$ Height $\times$ Block is not possible to estimate and therefore confounded with the error term. In model (2) the effect of $F \times T \times$ Block is confounded with the error term. Response variables analysed were ring width and ring density. Analyses were carried out using the GLM procedure in the SAS software package [1].

For each of the three four year periods, the effects of ring width and treatments per se on ring density were evaluated by a linear regression model. Input values were mean values per four-year period at 1.3 m based on plot mean values, i.e., for each regression growth rings of approximately the same age were used.

$$RD_{jkl} = \alpha + b_j + \beta_1 RW + \beta_2 F_k + \beta_3 T_l + e_{jkl} \qquad (3)$$

RD: ring density, α, β_1, β_2, β_3: constants, b: random effect for block, RW: ring width, F: fertilisation (0 = no fertilisation, 1 = fertilisation), T: thinning, (0 = no thinning, 1 = thinning).

The regression analysis was carried out using the GLM procedure in the SAS Software package [1].

3. RESULTS

Mean ring width over treatments and heights during the twelve-year period was 1.72 mm. For all of the four-year periods, the narrowest ring widths were produced at level 2 (*figure 1*) except for $F_1T_1$where the narrowest rings were produced at level 3. Mean ring density, weighted with mean ring width averaged over heights during the twelve-year period, was 384 kg m^{-3}. The highest densities occurred at levels 1 and 2. Level 4 showed the widest ring widths and the lowest ring densities (*figure 1*). At level 4 the radial trend of decreasing ring width and increasing ring density from pith to bark (data not shown) was more pronounced than at 1.3 m (*figure 2*).

Based on 12-year mean values from level 1–4 (model 1) there were increases in ring width from both fertilisation (+14%, p = 0.047) and thinning (+40%, p = 0.051) (*table II*). Mean ring density showed no significant differences following fertilisation (< 1%, p = 0.48) or thinning (–4%, p = 0.59). Height explained most of the variation in both ring width and ring density (p = 0.0001, *table II*). For ring width there was an interaction effect of thinning and height (p = 0.0014) expressing a decreased thinning effect on ring width with increasing height.

Based on four-year mean values at 1.3 m (model 2), no statistically significant differences were found between treatments before for the period prior to treatment (data not shown). In the first period following treatments there were significant increases in ring width from both fertilisation (24%, p = 0.023) and thinning (35%, p = 0.006) (*table III*). Ring density was not significantly affected by neither fertilisation (–2%, p = 0.47) nor thinning (–1%, p = 0.47). In the second period fertilisation significantly increased ring width (22%, p = 0.009) but did not change the ring density (+2%, p = 0.58). Thinning response during the second period was significant for both ring width (+22%, p = 0.005) and ring density (–5%, p = 0.020). During the last period fertilisation caused no significant effect on ring width (–7%, p = 0.17) and ring density (+3%, p = 0.45). Thinning increased ring width by 44% (p = 0.020) whereas ring density was not significantly affected (–4%, p = 0.12) during the third period.

Regressions of ring width, fertilisation, and thinning on ring density at 1.3 m based on mean values per plot for the three 4-year periods (model 3) showed a significant density decrease with increasing ring width (*table IV*). Effects of treatments per se were not significant when ring width was considered.

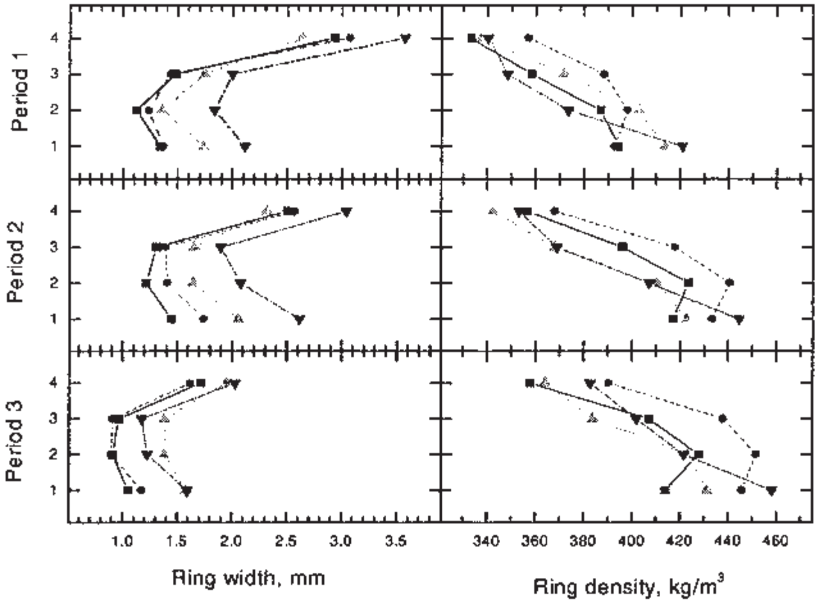

Figure 1. Period mean values for ring width (mm) and ring density (kg/m^3) for level 1–4 (1%, 1.3 m, 35%, and 65% of tree height, respectively). Period 1 = 1984–1987, period 2 = 1988–1991, period 3 = 1992–1995. ■ = control; F_0T_0, ● = fertilisation; F_1T_0, ▲ = thinning; F_0T_1, ▼ = fertilisation and thinning; F_1T_1. Each point represents mean value of four plots.

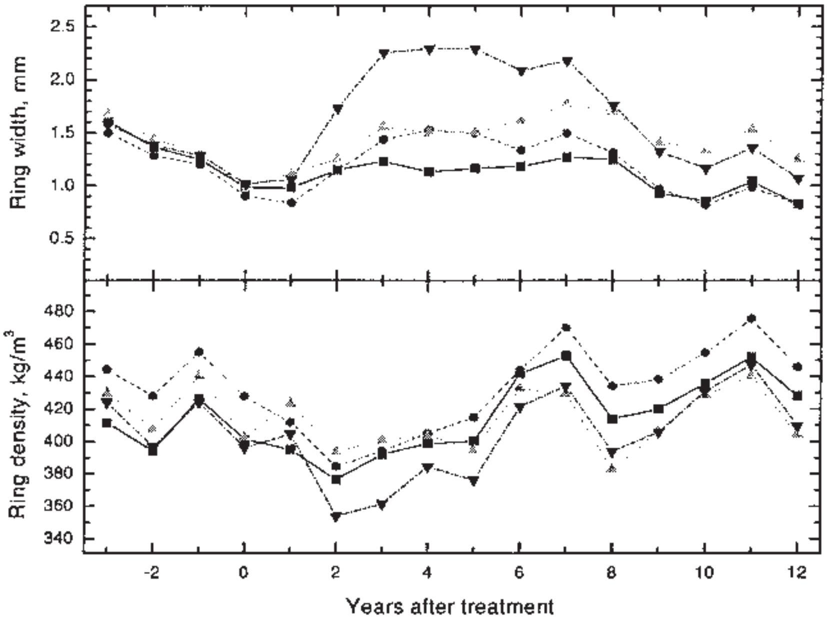

Figure 2. Ring width (mm) and ring density (kg/m^3) for individual years at 1.3 m. Year of treatment = year 0. ■ = control; F_0T_0, ● = fertilisation; F_1T_0, ▲ = thinning; F_0T_1, ▼ = fertilisation and thinning; F_1T_1. Each point represents mean value of six plots.

Table II. Analyses of mean ring width and mean ring density for the 1984–1995 period. Data from four blocks and from four different tree heights (1.3 m. 1%. 35%. and 65% of tree height). Mean ring density is calculated as: Σ (ring density × ring width)/ Σ ring width.

Variable	Variable *Df*	Variable *MS*	Denominator *Df*	Denominator *MS*	*F*-value	*P*-value
F						
Ring width	1	0.4666	3	0.0435	10.72	**0.0466**
Ring density	1	1.3800	3	2.1458	0.64	0.48
T						
Ring width	1	2.6124	3	0.2620	9.97	**0.051**
Ring density	1	0.6599	3	1.7758	0.37	0.59
F T						
Ring width	1	0.2081	3	0.3957	0.53	0.52
Ring density	1	1.4185	3	0.0313	45.26	**0.0067**
Height						
Ring width	3	4.6272	9	0.0337	137.18	**0.0001**
Ring density	3	10.8318	9	0.1937	55.92	**0.0001**
***F* Height**						
Ring width	3	0.0584	9	0.0178	3.28	0.073
Ring density	3	0.0461	9	0.4269	0.11	0.95
***T* Height**						
Ring width	3	0.1129	9	0.8862	12.74	**0.0014**
Ring density	3	0.6809	9	0.4422	1.54	0.27
***F T* Height**						
Ring width	3	0.0443	9	0.0156	2.84	0.098
Ring density	3	0.2007	9	0.4302	0.47	0.71
Block						
Ring width	3	0.0950	0.06	–0.0676	–1.41	**0.0000**
Ring density	3	0.2368	5.01	3.6451	0.065	0.98
***F* Block**						
Ring width	3	0.0435	3.03	0.3979	0.11	0.95
Ring density	3	2.1458	0.02	0.0281	76.42	0.92
***T* Block**						
Ring width	3	0.2620	2.90	0.3890	0.67	0.62
Ring density	3	1.7758	0.04	0.0433	41.03	0.85
***F T* Block**						
Ring width	3	0.3957	9	0.0156	25.37	**0.0001**
Ring density	3	0.0313	9	0.4302	0.073	0.97
Height Block						
Ring width	9	0.0337	1.73	0.0111	3.05	0.30
Ring density	9	0.1937	3.08	0.4389	0.44	0.85
***F* Height Block**						
Ring width	9	0.0178	9	0.0156	1.14	0.42
Ring density	9	0.4269	9	0.4302	0.99	0.50

Table II. (*continued*).

Variable	**Variable *Df***	**Variable *MS***	**Denominator *Df***	**Denominator *MS***	***F*-value**	***P*-value**
***T* Height Block**						
Ring width	9	0.0089	9	0.0156	0.57	0.79
Ring density	9	0.4422	9	0.4302	1.03	0.48
	Df	***SS***	***MS***	**R^2**	***F*-value**	***P*-value**
Model						
Ring width	54	20.748	0.384	0.99	24.63	**0.0001**
Ring density	54	60.871	1.127	0.94	2.62	0.061
Error						
Ring width	9	0.140	0.0156			
Ring density	9	3.872	0.4302			
Total						
Ring width	63	20.888				
Ring density	63	64.743				

Table III. Analyses of means of ring width (*RW*) and ring density (*RD*) at 1.3 m for the periods 1 (1984–1987), 2 (1988–1991), and 3 (1992–1995). Mean $RD = \Sigma\,(RD \times RW) / \Sigma\, RW$.

Variable	**Period**	**Variable *Df***	**Variable *MS***	**Denominator *Df***	**Denominator *MS***	***F*-value**	***P*-value**
F							
ring width	period 1	1	0.5240	5	0.0494	10.61	**0.023**
	period 2	1	0.5880	5	0.0344	17.11	**0.009**
	period 3	1	0.0435	5	0.0166	2.62	0.17
ring density	period 1	1	0.4009	5	0.6483	0.62	0.47
	period 2	1	0.1416	5	0.4051	0.35	0.58
	period 3	1	0.3392	5	0.5093	0.66	0.45
T							
ring width	period 1	1	1.0411	5	0.0495	21.05	**0.006**
	period 2	1	1.8223	5	0.0833	21.87	**0.005**
	period 3	1	0.9633	5	0.0841	11.45	**0.020**
ring density	period 1	1	0.0578	5	0.0956	0.60	0.47
	period 2	1	2.2374	5	0.1996	11.21	**0.020**
	period 3	1	1.2782	5	0.3743	3.42	0.12
F T							
ring width	period 1	1	0.2020	5	0.0495	4.09	0.10
	period 2	1	0.0855	5	0.0572	1.49	0.28
	period 3	1	0.0303	5	0.0247	1.23	0.32
ring density	period 1	1	1.6292	5	0.7021	2.32	0.19
	period 2	1	0.3992	5	0.3297	1.21	0.32
	period 3	1	0.6237	5	0.3951	1.58	0.26

Table III. (*continued*).

Variable	**Period**	**Variable *Df***	**Variable *MS***	**Denominator *Df***	**Denominator *MS***	***F*-value**	***P*-value**
Block							
ring width	period 1	5	0.1138	1.67	0.0495	2.30	0.36
	period 2	5	0.1193	1.60	0.0604	1.97	0.41
	period 3	5	0.0321	3.63	0.0760	0.42	0.82
ring density	period 1	5	0.2092	0.01	0.0418	5.00	0.97
	period 2	5	0.1594	1.21	0.2751	0.58	0.75
	period 3	5	0.3519	2.15	0.4885	0.72	0.67
F × **Block**							
ring width	period 1	5	0.0494	5	0.0495	1.00	0.50
	period 2	5	0.0344	5	0.0572	0.60	0.71
	period 3	5	0.0166	5	0.0247	0.67	0.66
ring density	period 1	5	0.6483	5	0.7021	0.92	0.53
	period 2	5	0.4051	5	0.3297	1.23	0.41
	period 3	5	0.5093	5	0.3951	1.29	0.39
T × **Block**							
ring width	period 1	5	0.0495	5	0.0495	1.00	0.50
	period 2	5	0.0833	5	0.0572	1.46	0.35
	period 3	5	0.0841	5	0.0247	3.41	0.10
ring density	period 1	5	0.0956	5	0.7021	0.14	0.98
	period 2	5	0.1996	5	0.3297	0.61	0.70
	period 3	5	0.3743	5	0.3951	0.95	0.52
		Df	***SS***	***MS***	***R*²**	***F*-value**	***P*-value**
Model							
ring width	period 1	18	2.8308	0.1573	0.92	3.18	0.10
	period 2	18	3.6807	0.2045	0.92	3.57	0.08
	period 3	18	1.7007	0.0945	0.93	3.83	0.07
ring density	period 1	18	6.8535	0.3808	0.66	0.54	0.85
	period 2	18	6.5988	0.3666	0.80	1.11	0.50
	period 3	18	8.4180	0.4677	0.81	1.18	0.46
Error							
ring width	period 1	5	0.2473	0.0495			
	period 2	5	0.2862	0.0572			
	period 3	5	0.1235	0.0247			
ring density	period 1	5	3.5104	0.7021			
	period 2	5	1.6483	0.3297			
	period 3	5	1.9753	0.3951			
Total							
ring width	period 1	23	3.0781				
	period 2	23	3.9669				
	period 3	23	1.8242				
ring density	period 1	23	10.3639				
	period 2	23	8.2471				
	period 3	23	10.3638				

Table IV. Regression of ring density on ring width (*RW*) at 1.3 m. Fertilisation *F* (0 = no fertilisation. 1 = fertilisation) and thinning *T* (0 = no thinning. 1 = thinning). Mean values per plot for each four-year period. Period 1 (1984–1987), period 2 (1988–1991), period 3 (1992–1995).

Fixed effects	**Variable**	***Df***	**Parameter estimate**	**Standard error**	***P*-value**
Period 1	*intercept*	1	484.49	65.66	0.0001
	RW	1	–55.53	29.92	0.0846
	F	1	–2.55	20.66	0.9035
	T	1	10.66	23.32	0.6545
Period 2	*intercept*	1	525.48	50.93	0.0001
	RW	1	–56.47	21.11	0.0181
	F	1	20.92	14.60	0.1738
	T	1	0.52	18.17	0.9775
Period 3	*intercept*	1	486.61	45.32	0.0001
	RW	1	–66.32	32.40	0.0599
	F	1	–6.73	15.65	0.6736
	T	1	–8.25	18.26	0.2571
Model	***Df***	***SS***	***MS***	R^2	***P*-value**
Period 1					
Model	8	6109	763.63		
Error	15	9645	643.03		
Total	23	15754		0.39	0.37
Period 2					
Model	8	9216	1151.99		
Error	15	5518	367.85		
Total	23	14734		0.63	0.027
Period 3					
Model	8	9226	1153.29		
Error	15	10133	675.56		
Total	23	19359		0.52	0.18

4. DISCUSSION

The basic density mean value found in this study is in accordance with earlier studies of *Pinus sylvestris* in Sweden [3, 8]. In the present study, density values are based on unextracted wood samples. Since growth rings analysed, i.e., 1980–1995, are all contained in the sapwood [21] the density contribution of extractives can be estimated to about 2–3% [9] and should therefore not significantly affect the density values. The overall pattern of increasing density from pith to bark, and decreasing *density* with increasing tree height is in accordance with earlier findings in even aged conifer stands [12, 19, 32]. From 1% tree height (level 1) to 1.3 m (level 2) there was no consistent decrease in wood density (*figure 1*). This might be attributed to larger ring width at 1% tree height than at 1.3 m.

Even though the treatment response at 1.3 m in ring width was significant in all periods for thinning and in period 1 and 2 for fertilisation, the treatment effects on ring density were moderate and only significant for thinning in the second four-year period (*table III*). An explanation could be that differences in radial growth between treatments were not large enough to affect ring density. Supporting this hypothesis is the fact that the only significant density response occurred in period 2 where growth increase was at its largest (*figure 1*). For period 2 minimum plot mean ring width was 0.69 mm (F_0T_0) and maximum ring width 2.44 mm (F_1T_1). Corresponding values for period 1 were 0.62 mm (F_0T_0) and 2.36 mm (F_1T_1), and 0.45 mm (F_0T_0) and 1.48 mm (F_1T_1) for period 3. Relative differences are considerable, but absolute differences are small. In general, effects of fertilisation and/or thinning treatments on ring density are generally less pronounced than effects on ring width [5, 8, 12, 19, 22].

Ring width and ring density were negatively correlated for both fertilisation and thinning (*table IV*). Since the regression was made using ring width and ring density data of the same cambial age (within each period) and at the same tree height, this relation is not confounded with the age and height trends within trees [13, 19]. There was no additional effect of thinning or fertilisation on ring density. This is in accordance with the result in *Picea abies* by Pape [24] who concluded that the decreased basic density following thinning were attributable to increased ring width alone. This indicates that the relation between ring density and ring width is consistent and does not change with treatment. However, one should bear in mind that in the present study, only one location was studied and that the relation between ring width and ring density is affected by differences in growth conditions. This may have implications also for other intra-ring characteristics. However, due to simultaneous counteracting changes in intra-ring characteristics (earlywood percentage, mean density of early- and/or latewood) following treatments there might be treatment effects on intra-ring characters even though mean ring densities are not changed [22, 32]. In conifers, decreasing ring density with increasing ring width is generally attributed to increasing proportion of early wood with increasing ring width [12, 13]. Even though ring width had a significant effect on ring density, a considerable part of the ring density was not explained by the regression model. This is probably due to genetic variability and influence of climatic variation [6].

The decreased density following fertilisation indicated in the study by Valinger et al. [29] was not found in this study (*figure 2*). Analysis of microdensity data of the outer 12 growth rings from discs at 1.3 m originating from the two blocks comprised in the study by Valinger et al. [29] showed no fertilisation effects on density. In the present study only stem discs from 1.3 m were analysed from the two blocks, whereas total stem biomass and stem volume were calculated in the former study. Since no proper weighing of ring density to ring basal area were performed in the present study direct density comparisons between the studies are not possible.

Results of this study show that the treatments did not profoundly change wood density and that relative changes in wood density were smaller than changes in radial growth. Changes in ring density were mainly attributed to increased ring width following treatments and not by treatment per se. The relation of decreasing ring density with increasing ring width found in the present study is not confounded with age of the cambium or position of growth ring in the tree since comparisons were made between rings of the same age at same height (cf. [7, 13, 16, 19, 27]). Since there is probably no genetic correlation between ring width and ring density [11, 19], the varying relation between ring width and ring density reported in literature might arise from adaptation to local conditions of mechanical stress [18], differences in growth conditions [6] or the methods used for evaluation [27].

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