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Influence of Silvicultural Regime on Wood Structure Characteristics and Mechanical Properties of Clear Wood in *Pinus sylvestris*

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The objective of the study presented here was to evaluate the influence of two contrasting silvicultural regimes on the structural characteristics and mechanical properties of different wood tissue types at different heights in Scots pine (*Pinus sylvestris* L.) trees, and reasons for these differences. Wood samples were taken from two stands (a dense 85-year-old stand established by direct seeding and a 56-year-old widely spaced stand established by planting, designated SDR and PWR, respectively in the boreal zone of Sweden). The wood properties associated with the examined silvicultural regimes differed, in terms of both structural characteristics (with up to fivefold differences between SDR and PWR) and mechanical properties (with up to almost threefold differences between SDR and PWR). Differences between the regimes were highest for stiffness, followed by strength and hardness properties and lowest for relative stiffness after 1000 h of loading (creep) (with higher parameter values for SDR than for PWR in each case). The rankings could be explained by differences among the mechanical properties in their sensitivity to maturation of wood characteristics. In conclusion, silvicultural regimes have great potential to regulate wood structural characteristics and mechanical properties, apparently due to the influences of the green crown and growth rate on the vascular cambium, the strength of which vary throughout the rotation period. A silvicultural regime could therefore be seen as a tool that can be used to select material qualities and to make wood a more homogenous material for engineers.

Keywords silvicultural regime, structural characteristics, mechanical properties
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1 Introduction

In recent decades, use of plastics and steel has increased at the expense of wood, due in large part to progress in material science regarding these materials. To make wood more competitive in the future, accurate estimates of wood structural and material properties are probably needed (cf. Bowyer 2000). In order to attain desired objectives a forest owner may perform certain silvicultural treatments, for instance to exploit the effects of competition between trees, and thus affect stem volume increment and tree- and wood properties. Regeneration approaches involving direct seeding or natural regeneration offer scope to produce denser and more heterogeneous stands than planting seedlings (Agestam et al. 1998). Competition begins earlier in dense, even-aged stands of light-demanding species like Scots pine (*Pinus sylvestris* L.) than in widely spaced stands, especially if the trees are of different sizes, leading to early differentiation into hierarchical classes (Nilsson and Albrektson 1994). After crown closure, light becomes limiting, and competition and differentiation into hierarchical classes is accentuated (Nilsson and Albrektson loc cit.), especially if the first cutting is late. High stem density may result in high stem volume yields in early stages of the rotation (Pettersson 1992), low proportions of green crown (Lindström 1996), thin annual rings, and great diversity in the two latter properties. Thinning from above, i.e., favouring trees with a low proportion of green crown and thin annual rings by removing dominant trees, may give higher profits than the conventional thinning from below, depending on prices and harvesting costs (cf. Eriksson 1990). Factors one should consider when choosing between thinning regimes are the growth rate and dimensions of dominant trees when the stand is young and the possible high value increments of old individuals that have grown slowly due to the associated wood properties (Axelsson and Eriksson 1986).

Consequently, the silvicultural treatments applied over time, i.e. silvicultural regimes, affect competition between single trees and thus promote certain green crown proportions and annual ring width patterns. Structural wood characteristics like annual ring width, green crown properties, cambial age and apical meristem age can be used to assess maturity in wood. For instance, juvenility in conifers is associated with thick annual rings, low density and latewood proportion, small cell diameter, thin cell walls, short cells and large microfibril angles (cf. Olesen 1982, Zobel and Buijtenen 1989, Kyrkjeeide 1990, Lindström 1996, Mencuccini et al. 1997, Bruchert 2000, Persson 2000, Amorasekara and Denne 2002, Groom et al. 2002, Mattsson 2002). The structural characteristics can also be used, at least to some extent, to predict material parameters such as stiffness (Mencuccini et al. 1997, Bao et al. 2001, Groom et al. 2002), bending strength (Bao et al. 2001, Raymond et al. 2004), Brinell hardness in tangential direction (Holmberg 2000, Raymond et al. 2004), Brinell hardness in longitudinal direction (Holmberg 2000), compression strength (Bao et al. 2001, Yang and Fortin 2001, Raymond et al. 2004) and creep (Hunt 1999, Groom et al. 2002). Wood tissue types are also predictive, e.g. heartwood content may have some effect on certain mechanical properties (Zobel and Buijtenen 1989), although a study of Kliger et al. (1995) found no effect of heartwood content on stiffness and modulus of rupture. Furthermore, structural characteristics have interactive effects on mechanical properties (Persson 2000). Therefore, the best predictions of mechanical properties are obtained by using several wood characteristics (Eriksson et al. 2005).

Since silvicultural regimes affect the green crown proportion and annual ring width, and these characteristics have strong effects on structural and mechanical properties, comparisons of trees with major differences in green crown proportions and annual ring width patterns will describe the potential of silvicultural regimes. Furthermore, comparisons between regimes should consider the effects of apical meristem age, cambial age and wood tissue type in order to describe the total range of properties within a tree/regime (cf. above) and to relate differences to different ages of the rotation period.

The objective of the study presented here was to evaluate the effects of two different silvicultural regimes on wood structure characteristics and mechanical properties in different wood tissue types at two different heights in the trees, and reasons for these differences. Analysed wood structure characteristics were age of the apical meristem, cambial age, annual ring width, density, latewood proportion, cell length, cell diameter, cell wall thickness and microfibril angle. Wood tissue types considered were heartwood and sapwood at stump height and intermediate top height of the tree. Tested mechanical properties were stiffness/modulus of elasticity, bending strength and creep (stiffness at 1000 h relative to initial) parallel to grain in bending, compression strength parallel to grain, and Brinell hardness at both tangential and longitudinal directions.

The first hypothesis was that the large expected differences in growth rate and proportion of green crown between the chosen regimes would be associated with substantial differences in wood structural and mechanical properties. The second hypothesis was that wood structural characteristics could explain the major differences in mechanical properties between the regimes. The third hypothesis was that green crown variables, such as the distance to or the proportion of green crown, in combination with annual ring width and age characteristics, could be used to explain the differences in wood structure over time between the regimes. To test these hypotheses, analyses were first carried out to quantify wood structural characteristics and mechanical properties among different wood types and heights in the trees. Then, characteristics were ranked, in order of importance, for explaining the differences in mechanical properties of different sub-groups between the regimes. Finally, linear regression analyses were carried out to test the predictions of annual ring width, density, cell length and width, cell wall thickness, latewood proportion and microfibril angle based on green crown, ring and age parameters.

2 Material and Methods

2.1 Sites

Wood samples were taken from Scots pine (*Pinus sylvestris* L.) trees in two stands subjected to very different silvicultural regimes (four 56-year-old trees from Vindeln Experimental Forests, Åheden, 64°09´N, 19°40´E, and four 85-year-old trees from a forest trial 2 km from Åheden established in 1918 by Edvard Wibeck), spanning a large part of the variation found within northern Fennoscandia. The soils are sand-silt tills in the Wibeck area and sediments of fine sand in the Åheden area. In both cases the moisture class is mesic. The site indices (Hägglund and Lundmark 1982) were T22 for the Wibeck area and T18 for the Åheden area. The main difference between the stands is that trees at Åheden were planted at wide spacing and since nine years old grown at a spacing of 10 m, and thus are dominant individuals, while the trees from the Wibeck area were established through sowing at dense spacing and are intermediate individuals. Another difference between the stands is that Wibeck is multi-storeyed because it was thinned from above, while Åheden is single-storeyed and has only been cleaned by pre-commercial thinning and herbicides. Consequently, in contrast to trees from the Wibeck stand, those at Åheden could be considered typical rapidly-grown trees without any crown closure. Samples from Wibeck are hence referred to as SDR (Seeding, Dense-spacing Regime) and samples from Åheden as PWR (Planting, Wide-spacing Regime). The treatment histories for the two regimes are summarised in Table 1.

2.2 Sampling Procedure

Stem sections, 35 cm long in longitudinal direction, were taken from stump height and intermediate top height between two branch whorls 20 and 30 year up in Åheden and Wibeck trees, respectively). Samples were taken from these stem sections for analysing the following mechanical properties: stiffness, bending strength and creep parallel to grain in bending, Brinell hardness and compression strength parallel to grain and Brinell hardness at tangential direction. Approximately 100 independent samples were tested in the analyses of each mechanical property. Samples were taken to represent specific cambial ages (i.e. comparisons were made between samples at different radii within a stem section) and specific ages of apical meristem (i.e. samples from lower and upper stem sections of the trees were compared). Samples from both sections with cambial ages of 6, 11, 15, 20, 26, 33 and 42 years (except lower stem sections with a cambial age of six

Table 1. Treatment history of the PW- and SD-regimes.

Regime	Year	Silvicultural activities
PWR	1948	Establishment of a widely spaced seed-tree shelter of Scots pine, cleaning, and planting of two-year-old pine seedlings at a spacing of 3 m.
	1952	Pre-commercial thinning in which all birches (*Betula pubescens)* were cut.
	1953	Harvesting of seed-trees, and herbicide treatment of birches.
	1954	Cleaning of pre-grown spruce (*Picea abies*) and pine, herbicide treatments of birch and aspen, (*Populus tremula*), pre-commercial thinning of herbicide-treated birches.
	1957	Herbicide treatments of birch and aspen. Sample trees have since grown at a spacing of 10 m.
SDR	1918	Clear felling and establishment of a tree shelter with a density of 40 trees * ha^{-1}.
	1918	Soil scarification and direct seeding of pine.
	1930	Census showed that the stand contained 15 180 seedlings * ha^{-1} of which 11 077 pine with an average height of 47 cm.
	1935	Harvest of the overstorey shelter trees.
	1954	Census showed that the stand contained 11 695 trees * ha^{-1}, of which 4870 trees * ha^{-1} were pines with an average dbh of 8.9 cm and height of 8.1 m.
	1963	Pre-commercial thinning of the very dense stand.
	1967	Thinning.
	1983	Thinning.
	1989	Thinning.
	1993	The stand was thinned from above, 20.9% of the volume was harvested and after thinning the stem density was 1425 trees * ha^{-1}.
	1994	Thinning of a few trees damaged by snow.
	1999	Thinning of a few trees damaged by snow.

and PWR upper stem sections of 42 years) were tested. Heartwood and sapwood were visually distinguished on the basis of the generally darker appearance of heartwood. From each stem section for each cambial age tested, two samples were taken for bending, one for compression strength, one for Brinell hardness at longitudinal direction and one for Brinell hardness at tangential direction analyses. The samples consisted of clear wood without structural defects. Bending samples from stump height stem sections occasionally contained defects, but only at positions where stress was low. For five bending samples with non-straight grains, it was necessary to correct the measured values using a modified form of the equation developed by Hankinson (in Dinwoodie 2000) to estimate the stiffness and bending strength values the samples would have had if they were straight grained.

During preparation, wood samples were frozen and kept in plastic bags to keep water content above the fibre saturation point. During the conditioning and testing procedures the air temperature was kept at 20 °C ± 0.5 °C and at a relative humidity of 65% ± 1% in climate chambers. Before measurement, wood was conditioned until results of two weighings of the mass of the test piece, carried out at an interval of 6 h, did not differ by more than 0.1% (EN 408 1995).

2.3 Bending Properties

Four-point-bending tests were applied to samples (120.5 mm long, 6.3 mm high and three annual rings wide, in longitudinal, tangential and radial directions, respectively) for stiffness, bending strength and creep determinations. Stiffness and bending strength were tested in a Hounsfield 5000 Universal Testing Instrument, while MOE_{t1000h} (creep) was determined in an apparatus using hanging weights, applying about 20% of the maximum stress. Pieces of wood 6 mm in length were glued to sides of the thinnest samples of creep, with a width of less than 3 mm, to by their supports, prevent tilting. Mechanical properties were tested and calculated using the four-point-bending protocol described by EN 408 (1995).

2.4 Compression Strength

Samples for compression strength analyses had a radial dimension of three annual rings width and tangential dimensions that were equal to radial dimensions when the latter were ≤6.3 mm, and 6.3 mm when the annual rings were wide enough for the radial dimensions to exceed 6.3 mm. Longitudinal dimensions were six times the smaller of the two transverse dimensions. The testing machine was a Hounsfield 5000 Universal Testing Instrument. The compression strength parameter was tested and calculated according to EN 408 (1995).

2.5 Brinell Hardness

Samples for tests of Brinell hardness at longitudinal direction had dimensions of 20 mm in longitudinal direction while samples for tests of Brinell hardness at tangential direction had dimensions of 20 mm in tangential direction. Hardness was measured according to Brinell (Mörath 1932) with one exception; diameter was measured only in the radial direction according to Holmberg (2000). All measurements were done using a steel ball of 10 mm diameter and load of 490.5 N in the Hounsfield 5000 Universal Testing Instrument. The maximal load, F, was reached within 15 sec, kept constant over a period of 30 sec, and then reduced to zero within another 15 sec. Subsequently, without any further preparation of the sample, the indentation diameter was measured by help of light microscopy. Brinell hardness H_B (N/mm^2) is given by Eq. 1:

$$H_B = 2F/(\pi D(D - \sqrt{D^2 - d^2})) \tag{1}$$

where F (N) is applied load, D (mm) the diameter of the steel ball and d (mm) the diameter of indentation.

2.6 Measurement of Ring and Fibre Characteristics

For each cambial age of interest, one sample used for testing creep from each stem section was also used for the cell morphology, late wood proportion and microfibril angle measurements. Annual ring width and density were analyzed in every sample used for testing any mechanical property. The measured latewood proportions of samples used for testing creep were used to estimate the latewood proportions in comparable samples (i.e. samples of the same cambial age from the same stem section) used for testing other mechanical properties, by adjusting according to the difference in density between them. The specific relationships between proportion of latewood and density found within each wood tissue type and vertical position in the trees were used to derive the required adjustment factors. No adjustments were needed in analyses of cell morphology parameters.

Tracheid length (mean measured length-weighted contour length), cell wall thickness and cell width measurements were determined using a Kajaani FiberLab 3.5 optical fibre dimension analyser (Metso Automation Inc.) and the maceration method described by Franklin (1945). Microfibril angle was determined using light microscopy, after repeated hydration-dehydration (water bath and drying at 140 °C) cycles and iodide staining of macerated cells, for more information see Eriksson et al. (2005). The staining was according to Senft and Bendtsen (1985), except that the period of immersion was 40 minutes and the samples were macerated cells. Microfibril angle was calculated from the mean angles of 20 earlywood cells and 10 latewood cells and the measured proportion of latewood in each sample. Parameters with increased proportional weights (four-fold and six-fold, as shown in Eq. 2 and Eq. 3, respectively) of latewood cells' microfibril angles (Mfa_{Lw}) were tested to evaluate whether angles of latewood cells are more important than angles of earlywood (Mfa_{Ew}) cells in predictions of mechanical properties (cf. Senft and Bendtsen 1985). Where Lw is the proportion of latewood and Ew is the proportion of earlywood.

$$Mfa\,(4) = (4 * Mfa_{Lw} * Lw + (1 - Lw) * Mfa_{Ew}) / (1+3 * Lw) \tag{2}$$

$$Mfa\,(6) = (6 * Mfa_{Lw} * Lw + (1 - Lw) * Mfa_{Ew}) / (1 + 5 * Lw) \tag{3}$$

Transverse sections (20 μm thick) were cut using a sledge microtome to measure fibre type (latewood or earlywood). The proportion of latewood in the samples was measured using light microscopy and Mork's (1928) definition, under which the transition to latewood occurs when the diameter of the lumen is less than twice the double cell wall thickness. Annual ring width was measured by digital calipers (±0.01 mm). Density was determined by measuring the weight and volume of the samples with a resolution of 0.1%, the volume

Table 2. Functions predicting stiffness (MOE), bending strength (f_m), Brinell hardness in tangential direction ($H_{B,90}$), Brinell hardness in longitudinal direction ($H_{B,0}$), compression strength (f_c) and creep (relative stiffness$_{t1000h}$). Predictors are variables that are significantly ($p \leq 0.05$) correlated with a mechanical property.

Equation	Predictor (Sign. p ≤ 0.05)	S	R-Sq (adj)
MOE = –13968 + 8724 Hw – 53.8 Hw * Aca – 374 Hw * Rw – 13969 Hw * D – 36.8 Aca + 18863 D – 32.9 Aap + 6112 Lw + 98361 Cwt/Cd – 55560 Cwt/(Cd * Cl) + 22556 1/Mfa6	Con, Hw, Hw * Rw, Hw * D, Aca, D, Aap, Lw, Cwt/Cd, Cwt/(Cd * Cl), 1/Mfa(6)	970	0.93
f_m = 1048 – 148 Hw * D + 53.4 Hw * Lw + 18.4 Hw * Cl – 4.70 Hw * Cd + 36.5 Hw * Cwt + 0.814 Hw * Mfa – 0.328 Aca – 11.6 logRw + 233 D + 59.7 Cl^2 + 0.200 Cd^2 – 82.8 Cwt – 453 Cl + 87.8 1/Mfa(6) – 9941 Cwt/(Cd * Cl) + 27206 Cwt/(Cd * Cl)^2 + 16244 (Cwt/Cd)^2	Con, Hw * D, Aca, D, Cl$^{2\cdot}$ Cl, Cwt/(Cd * Cl), (Cwt/(Cd * Cl))$^{2\cdot}$, (Cwt/Cd)^2	7.9	0.91
$H_{B,90}$ = –721 + 1.93 logAap – 19.2 Hw + 1.26 Hw * Rw + 27.2 Hw * D + 6.81 Hw * Cl + 1.11 Hw * Cd – 10.4 Hw * Cwt – 18.8 D – 16.2 Cl + 9.28 Cd – 57.8 Cwt – 896 Cwt/(Cl * Cd)+ 9467 Cwt/Cd + 3480 (Cwt/(Cd * Cl))^2 – 26342 (Cwt/Cd)^2 – 5.21 logRw + 0.143 Mfa(6) – 172 1/Mfa + 158 1/Mfa(6) – 7.79 1/D –0.000374 Cd^3	Con, Hw, Hw * Rw, Hw * D, Hw * Cl, Hw * Cd, Hw * Cwt, D, Cl, Cd, Cwt, Cwt/(Cl * Cd), Cwt/Cd, (Cwt/(Cd * Cl))$^{2\cdot}$ (Cwt/Cd)$^{2\cdot}$ logRw, 1/Mfa, 1/Mfa(6), 1/D	1.4	0.82
$H_{B,0}$ = 106 + 101 D – 152 Cl + 15.3 Cd – 0.135 Aap – 2.24 Hw * Rw – 62.7 Hw * D + 0.297 Hw * Mfa + 1.22 Hw * Cd – 6152 Cwt/(Cl * Cd) + 23275 (Cwt/(Cd * Cl))^2 + 39601 Cwt/Cd^2 – 0.159 Cd^2 – 12003 Cwt/(Cd^2 * Cl^2) – 285 1/Mfa + 243 1/Mfa(6) – 10.0 logAca + 3.79 Cl^3	D, Cl, Hw * Rw, Hw * D, Hw * Cd, Cwt/(Cl * Cd), Cwt/(Cd * Cl))$^{2\cdot}$ Cwt/Cd$^{2\cdot}$ 1/Mfa(6), logAca, Cl^3	3.7	0.88
f_c = –1.5 – 0.385 Hw * Aca + 46.9 Hw * D + 2.65 Hw * Cd – 21.5 Hw * Cwt – 24.6 Cl – 47.4 Cwt + 30.1 Lw – 1.86 Mfa + 1.95 Mfa(4) – 286 1/Mfa + 303 1/Mfa6 – 1675 Cwt/(Cl * Cd) + 1909 Cwt/Cd + 11003 (Cwt/(Cd * Cl))^2 + 0.103 Cd^2 – 20218 Cwt/(Cd^2 * Cl^2) – 2.57 logAap	Hw * Aca, Hw * D, Hw * Cd, Hw * Cwt, Cl, Cwt, Lw, Mfa, Mfa(4), 1/Mfa, 1/Mfa6. Cwt/(Cl * Cd), Cwt/Cd, (Cwt/(Cd * Cl))$^{2\cdot}$ Cd$^{2\cdot}$ Cwt/(Cd^2 * Cl^2)	2.8	0.90
Creep = 3.08 – 0.00493 Aap – 0.00792 Hw * Aca – 0.631 Hw * D + 0.112 Hw * Cwt – 0.00342 Aca – 0.190 D + 0.167 Cl – 0.143 Cd + 0.352 Lw + 0.00249 Cd^2 – 2.98 Cwt/Cd + 0.0504 Mfa(4) – 0.0525 Mfa(6) + 9.27 1/Mfa – 7.48 1/Mfa(4)	Aap, Hw * Aca, Hw * D, Hw * Cwt, Aca, D, Cl, Cd, Lw, Cd$^{2\cdot}$ 1/Mfa, 1/Mfa(4)	0.041	0.83

Note: S, standard deviation; Con, constant; Aap, age of apical meristem; Hw, heartwood; Aca, cambial age; Rw, annual ring width; D, density; Cl, cell length; Cd, cell diameter; Cwt, cell wall thickness; Lw, latewood proportion; Mfa, microfibril angle; Mfa(4) and Mfa(6), microfibril angle with a four-fold [Mfa(4)] and six-fold [Mfa(6)] weighting relative to Mfa_{lw}, respectively.

being determined using the water-displacement method.

2.7 Statistical Analyses

All wood structural characteristics were analysed for each sample that was subjected to any mechanical property test(s), and each mechanical property was measured in approximately one hundred independent samples. Analysis of variance, ANOVA, using the General Linear Model in MINITAB 13 (Minitab Inc 2000), was carried out to test if the regimes resulted in statistically significant different ($p \leq 0.05$) values for wood structural characteristics and mechanical properties. The influence of wood tissue type and height in the tree were also considered. The model included the components; Sample, Stand, Sample * Stand, Tree (Stand). Response values from the two regimes were compared for each combination of wood tissue type and height. Components were random except that Stand was fixed and Tree was nested within Stand. Figures for stiffness are used to illustrate the differences in mechanical properties between wood from the two regimes, and the relationships between the wood's structural characteristics and mechanical properties. Residuals against fit, normality and optimization of r^2 values were used to optimize the mathematical form of the structure parameters, and r^2 values were also used to test if specific wood structure parameters should be incorporated in an equation. Characteristics were then ranked in order of importance of their contributions to the differences in mechanical properties between the regimes for each type of wood tissue and each tested height in the trees. The equations that best predicted mechanical properties from structural characteristics presented in Eriksson et al. (2005) were used for ranking the characteristics (Table 2). Used values on characteristics were not equal in samples for test of different mechanical properties (Tables 3 and 4). The accuracy of the best predictive equations was tested by evaluating the r^2 values and the similarity between calculated and observed differences in mechanical properties between the regimes. Tests were also performed of the similarity between observed and calculated differences in compression strength when individual cell morphological characteristics were separated or total sum of them were used in the calculations. Finally, linear regression, using MINITAB 13 (Minitab Inc 2000), was carried out to test the prediction of annual ring width, density, cell length and diameter, cell wall thickness, latewood proportion and microfibril angle based on green crown, ring and age parameters.

3 Results

3.1 Wood Structural Characteristics

Differences in sample means between the two regimes were substantial (Table 3): fivefold for proportion of late wood (SDR higher), fourfold for distance to green crown (SDR higher), threefold for annual ring width (SDR lower), twofold or more for microfibril angle and proportion of green crown (SDR lower), and 50% to 10% for the other structural characteristics (SDR higher). The largest differences between SDR and PWR in means for all characteristics were found in sapwood (more than two-fold at both stump and intermediate top heights) while the differences were about 50% in heartwood (for both heights). Differences between the regimes for each characteristic were thus greater in sapwood than in heartwood. They also generally decreased from the stump- to intermediate top- vertical position (except for microfibril angle, annual ring width and density).

3.2 Mechanical Properties

In relation to PWR, based on means for all samples, SDR had ~150% higher stiffness, ~70% higher bending strength, about 50% higher compression strength, ~30% higher Brinell hardness at both tangential and longitudinal directions and ~10% higher relative stiffness (creep) (Table 5). Differences in mechanical properties in general between SDR and PWR were greater in sapwood than in heartwood, especially at stump height with an almost two-fold difference for sapwood at stump height, and about 50% higher values for the other subgroups. Differences in stiffness, bend-

Table 3. Mean values of wood structural characteristics in samples used for testing stiffness & bending strength from the SD and PW regimes (SDR and PWR, respectively) and the ratio of values (SDR/PWR).

Structural characteristics	SHW			SSW			THW			TSW			Total		
	SDR	PWR	SDR/PWR	SDR	PWR	SDR/PWR	SDR	PWR	SDR/PWR	SDR	PWR	SDR/PWR	SDR	PWR	SDR/PWR
Proportion of green crown	0.31a	0.75b	0.41	0.31a	0.75b	0.41	0.31a	0.75b	0.41	0.31a	0.75b	0.41	0.31a	0.75b	0.41
Distance to green crown (m)	10a	3.2b	3.3	10a	3.2b	3.3	4.9a	0.80b	6.0	4.9a	0.80b	6.0	7.6a	2.0b	3.9
Age of apical meristem (y)	13a	11a	1.2	15a	10b	1.5	37a	23b	1.6	36a	23b	1.6	26a	17b	1.5
Cambial age (y)	15a	17a	0.93	32a	34a	0.94	7a	8.1a	0.86	25a	23a	1.1	23a	22a	1.0
Annual ring width (mm)	1.8a	2.4a	0.78	0.78a	4.2b	0.19	2.2a	4.8b	0.46	0.91a	3.7b	0.25	1.2a	3.6b	0.33
Density (kg/dm^3)	0.57a	0.55a	1.0	0.60a	0.48b	1.3	0.47a	0.41a	1.2	0.57a	0.43b	1.3	0.57a	0.47b	1.2
Cell wall thickness (µm)	3.9a	3.6b	1.1	4.6a	4.1b	1.1	4.1a	3.8a	1.1	4.4a	4.0b	1.1	4.3a	3.9b	1.1
Cell diameter (µm)	27a	26b	1.1	32a	28b	1.1	28a	26a	1.1	30a	28b	1.1	30a	27b	1.1
Cell length (mm)	1.7a	1.3b	1.4	2.2a	1.7b	1.3	1.9a	1.6a	1.2	2.7a	2.2a	1.2	2.3a	1.8b	1.3
Proportion latewood	0.11a	0.030b	3.5	0.26a	0.048b	5.4	0.14a	0.007a	-	0.26a	0.069b	3.7	0.21a	0.045b	4.8
Microfibril angle (°)	21a	29b	0.74	9.8a	27b	0.37	17a	23b	0.72	8.7a	20b	0.44	12a	24b	0.51
Mean relative diff. (without age and green crown parameters)	-	-	1.5	-	-	2.6	-	-	(1.3)	-	-	2.1	-	-	2.1

Note: SHW, stump heartwood; SSW, stump sapwood; THW, intermediate top heartwood; TSW, intermediate top sapwood; Total, means for all samples. Different letters after the values denote significant differences, $p \leq 0.05$. The mean relative difference is the mean of the transformed characteristic's SDR/PWR ratio, excluding green crown, age of apical meristem and age of cambium parameters. The transformation was applied if the corresponding characteristic's ratio was lower than 1 in order to generate values >1.

Table 4. Mean values of wood structural characteristics in samples of subgroups for tests of compression strength, Brinell hardness at longitudinal direction, Brinell hardness at tangential direction and creep, which were used to explain differences in mechanical properties between SDR and PWR. For abbreviations, see Table 3.

Wood characteristic	SHW		SSW		THW		TSW	
	SDR	PWR	SDR	PWR	SDR	PWR	SDR	PWR
Compression strength								
Age of apical meristem (y)	14	9.6	13	10	38	23	35	23
Cambial age (y)	15	18	-	-	8.7	8.1	-	-
Density (kg/dm^3)	0.56	0.52	-	-	0.46	0.41	-	-
Cell length (mm)	1.7	1.3	2.2	1.7	2.0	1.6	2.8	2.2
Cell diameter (µm)	27	26	32	29	28	26	30	28
Cellwall thickness (µm)	3.9	3.7	4.6	4.1	4.1	3.8	4.4	4.0
Proportion of latewood	0.11	0.024	0.30	0.077	0.11	0.004	0.34	0.075
Microfibril angle (°)	22	29	9.1	26	15	23	8.3	20
Brinell hardness at longitudinal direction								
Age of apical meristem (y)	12	9.8	14	10	37	23	36	23
Cambial age (y)	16	18	33	36	8.1	8.1	24	22
An. ring width (mm)	1.8	2.5	-	-	2.1	4.9	-	-
Density (kg/dm^3)	0.58	0.56	0.63	0.49	0.48	0.41	0.56	0.44
Cell length (mm)	1.7	1.3	2.2	1.7	2.0	1.6	2.7	2.2
Cell diameter (µm)	27	26	32	29	28	26	30	28
Cellwall thickness (µm)	3.9	3.6	4.6	4.1	4.1	3.8	4.5	4.0
Microfibril angle (°)	21	29	9.3	26	15	23	8.6	20
Brinell hardness at tangential direction								
Age of apical meristem (y)	13	9.5	15	10	37	23	36	23
An. ring width (mm)	1.9	2.6	0.68	4.1	2.1	4.9	0.96	3.8
Density (kg/dm^3)	0.55	0.59	0.66	0.48	0.48	0.41	0.56	0.44
Cell length (mm)	1.7	1.3	2.2	1.7	2.0	1.6	2.7	2.2
Cell diameter (µm)	27	26	32	29	28	26	30	28
Cellwall thickness (µm)	3.9	3.6	4.6	4.1	4.1	3.8	4.5	4.0
Microfibril angle (°)	21	29	9.3	26	15	23	8.6	20
Creep								
Age of apical mer. (y)	16	9.7	16	9.5	38	23	38	23
Cambial age (y)	15	17	32	35	8.5	8.5	27	24
Density (kg/dm^3)	0.62	0.56	0.61	0.54	0.50	0.42	0.58	0.44
Cell length (mm)	1.8	1.2	2.2	1.6	2.0	1.6	2.8	2.2
Cell diameter (µm)	28	26	32	29	28	26	30	28
Cellwall thickness (µm)	3.9	3.6	4.6	4.2	4.1	3.8	4.4	4.1
Proportion of latewood	0.14	0.040	0.25	0.043	0.16	0.005	0.27	0.081
Microfibril angle (°)	18	29	9.5	28	14	23	8.6	19

ing strength and compression strength between the regimes were also greater in sapwood than in heartwood, especially at stump level. Differences in Brinell hardness at both tangential and longitudinal directions between the regimes were similar in rank among the subgroups, except that differences in heartwood were greater at intermediate top height than at stump height. The differences in creep between the regimes were greatest in sapwood at stump height, intermediate in heartwood at both heights and smallest in sapwood at intermediate top height.

Calculated differences in compression strength between the regimes deviated more from observed values when each cell morphological characteristic was separated in the calculation compared to when total sum of cell morphological characteristics was used (Fig. 1, heartwood at intermediate top height).

In heartwood at stump height, the characteristics that made major contributions to the higher stiffness, bending strength and compression strength values in SDR (Figs. 1, 2 and 3) were cell morphological characteristics and the proportion of latewood (compression strength). In sapwood at stump height, the contributing characteristics for differences in stiffness and bending strength were density, while for stiffness and compression strength microfibril angle, proportion of latewood and cell morphological characteristics also contributed. In heartwood at intermediate top height, major differences in compression strength, stiffness and bending strength between the regimes were found, attributable to differences in proportion of latewood and cell morphological characteristics. In sapwood at intermediate top height, the major contributing variables were microfibril angle, density (stiffness and bending strength), proportion of latewood (stiffness and compression strength) and cell morphological characteristics (stiffness). Characteristics that made major contributions to the stronger differences between the regimes in sapwood than heartwood were microfibril angle (for stiffness, compression strength and bending strength), density and annual ring width (for stiffness and bending strength) and proportion of latewood (for compression strength and stiffness). Differences in cell morphological characteristics were the major reasons for the higher differences between regimes at stump height than at intermediate top height.

In heartwood at stump height, the characteristics that made major contributions to the higher Brinell hardness (at both tangential and longitudinal directions) values in SDR (Figs. 4 and 5) were cell morphological characteristics. In sapwood at stump height, the contributing characteristics were microfibril angle, density (Brinell hardness at longitudinal direction) and annual ring width (Brinell hardness at tangential direction). In heartwood at intermediate top height, differences in Brinell hardness (at both directions) between the regimes were mainly explained by differences in cell morphological characteristics and density and

Table 5. Mean values of mechanical properties. The mean relative difference is the mean of the corresponding property's SDR/PWR ratio. For abbreviations and further information, see Table 2 and 3.

Mechanical property	SHW			SSW			THW			TSW			Total		
	SDR	PWR	SDR/ PWR	SDR	PWR	SDR/ PWR	SDR	PWR	SDR/ PWR	SDR	PWR	SDR/ PWR	SDR	PWR	SDR/ PWR
MOE (MPa)	6900a	2800b	2.5	11000a	3300b	3.3	6600a	3700b	1.8	11000a	4900b	2.2	9500a	3800b	2.5
f_m (MPa)	83a	57b	1.5	110a	58b	1.9	75a	56b	1.4	100a	59b	1.8	99a	58b	1.7
$H_{B,0}$ (N/mm^2)	45a	33b	1.4	53a	29b	1.8	41a	26b	1.6	48a	30b	1.6	48a	30b	1.6
$H_{B,90}$ (N/mm^2)	15a	14a	1.1	19a	12b	1.6	14a	9.6a	1.4	15a	11b	1.4	16a	12b	1.3
f_c (N/mm^2)	34a	23b	1.5	43a	25b	1.7	33a	24a	1.4	40a	25b	1.6	38a	24b	1.6
Creep (relative stiffness$_{1000h}$)	0.69a	0.58b	1.2	0.77a	0.64b	1.2	0.78a	0.77a	1.0	0.79a	0.79b	1.0	0.76a	0.70b	1.1
Mean relative difference	-	-	1.5	-	-	1.9	-	-	1.4	-	-	1.6	-	-	1.6

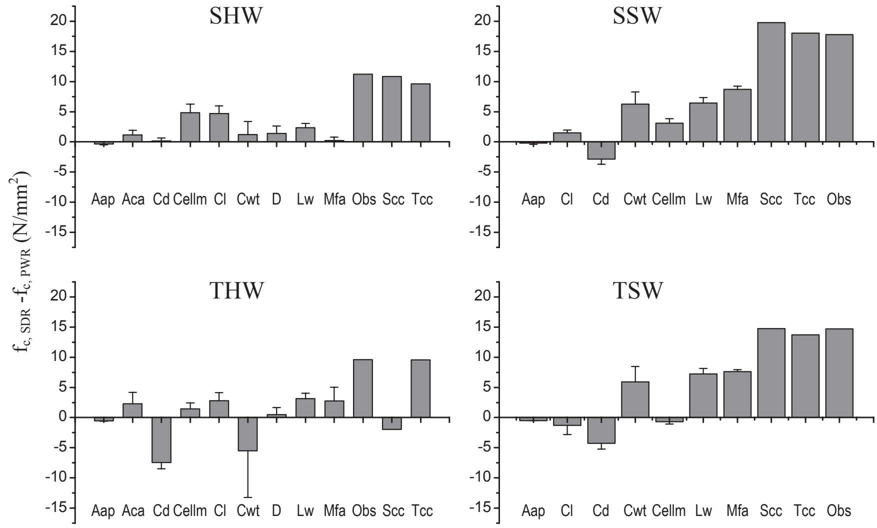

Fig. 1. Differences in compression strength (bars show standard errors) between SD- and PW-regimes in relation to different structural parameters in heartwood (…HW) and sapwood (…SW) at stump (S…) and intermediate top (T…) heights in the trees. Aap, age of apical meristem (y); Aca, cambial age (y); D, density (kg/dm^3); Cl, cell length (mm); Cd, cell diameter (µm); Cwt, cell wall thickness (µm); Lw, proportion of latewood; Mfa: microfibril angle (°); Cellm, the sum of Cl, Cd and Cwt; Scc, separate calculation of cellm. parameters in the calculation of the sum difference; Tcc, total sum of cell morphological differences in the calculation of the sum difference; Obs, observed sum difference. For mean values of the structural parameters, see Table 4.

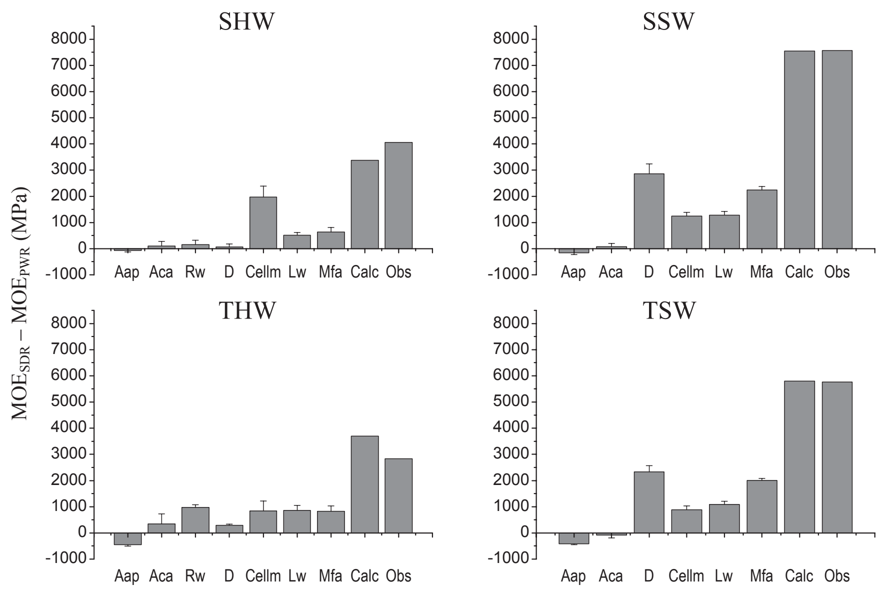

Fig. 2. Differences in stiffness (bars show standard errors) between SD- and PW-regimes in relation to different structural parameters. Rw, annual ring width (mm); Calc, calculated difference in mechanical property. For more abbreviations and further information, see Fig. 1. For mean values of the structural parameters, see Table 3.

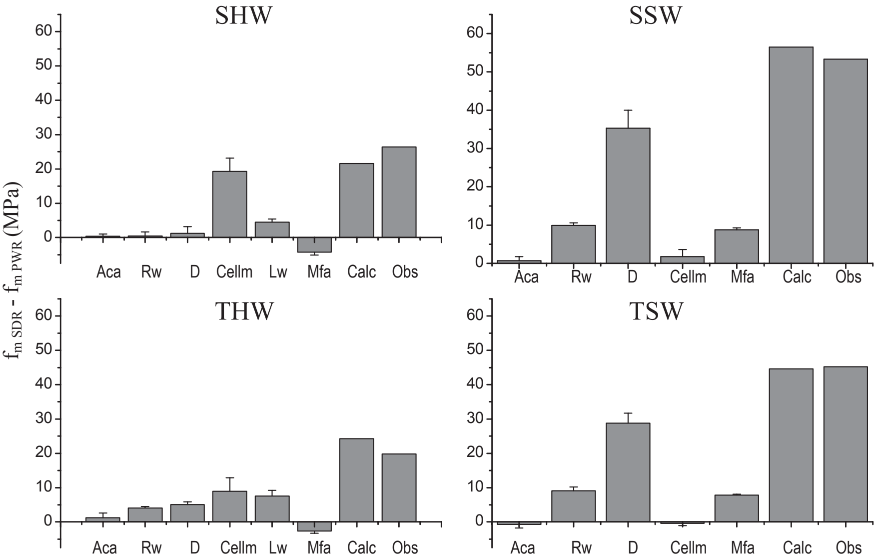

Fig. 3. Differences in bending strength (bars show standard errors) between SD- and PW-regimes in relation to different structural parameters. For abbreviations and further information, see Figs. 1 and 2. For mean values of the structural parameters, see Table 3.

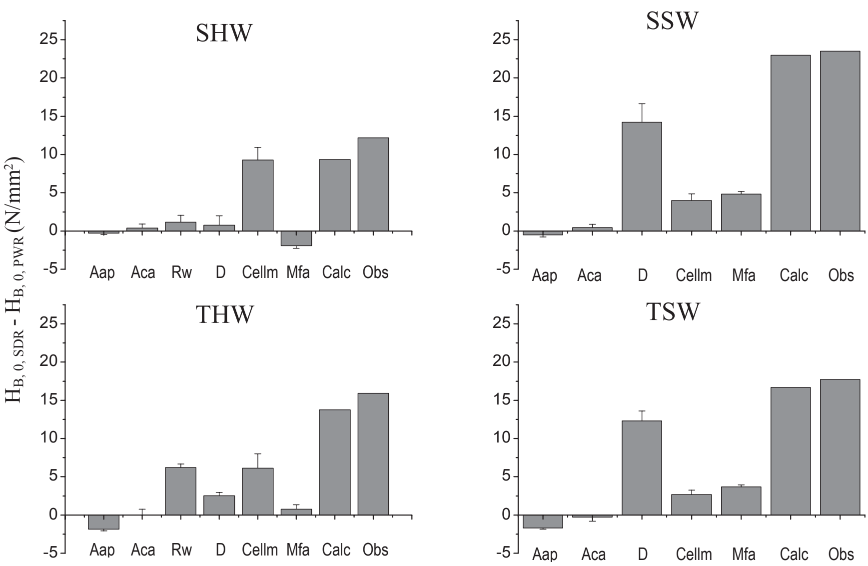

Fig. 4. Differences in Brinell hardness at longitudinal direction (bars show standard errors) between SD- and PW-regimes in relation to different structural parameters. For abbreviations and further information, see Figs. 1 and 2. For mean values of the structural parameters, see Table 4.

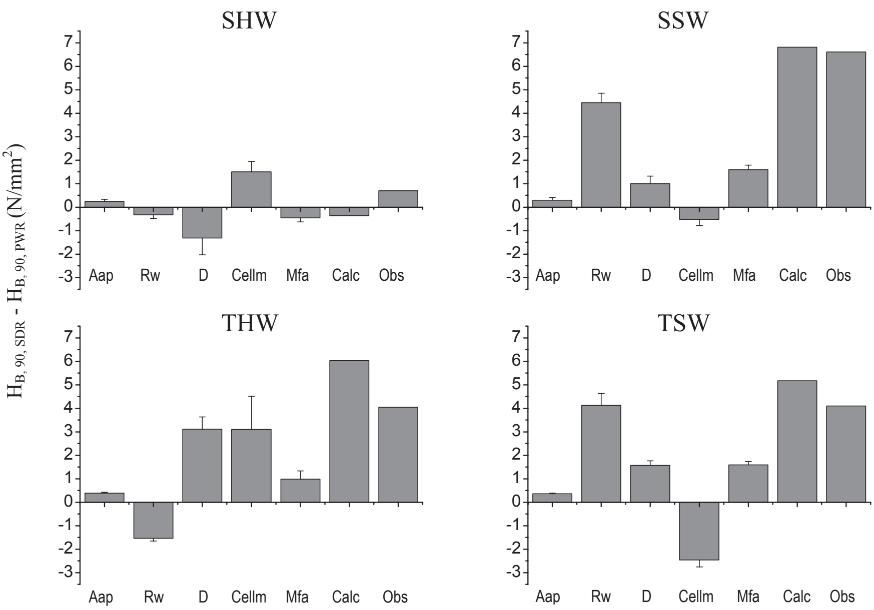

Fig. 5. Differences in Brinell hardness at tangential direction (bars show standard errors) between SD- and PW-regimes in relation to different structural parameters. For abbreviations and further information, see Figs. 1 and 2. For mean values of the structural parameters, see Table 4.

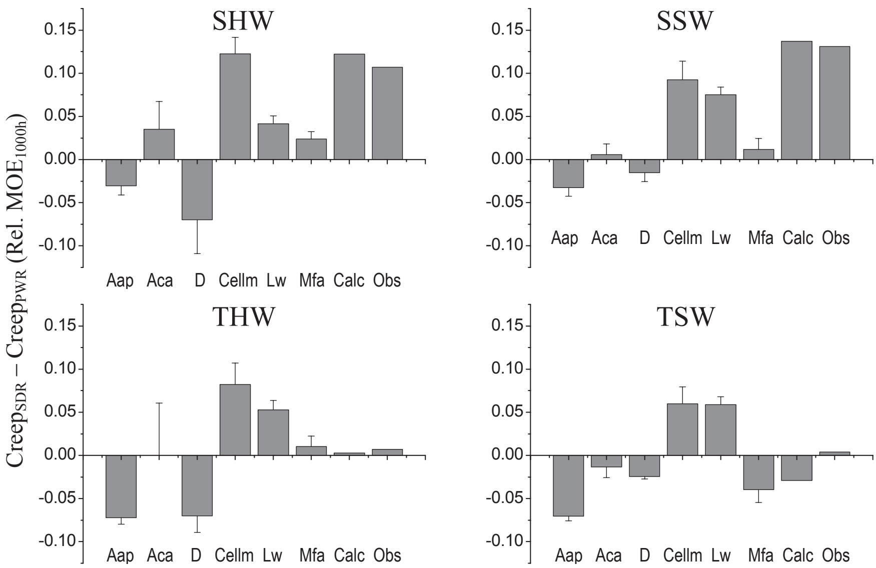

Fig. 6. Differences in creep (bars show standard errors) between SD- and PW-regimes in relation to different structural parameters. For abbreviations and further information, see Figs. 1 and 2. For mean values of the structural parameters, see Table 4.

Table 6. Functions predicting wood structure characteristics.

Equation (Gc+Rw)	Predictor sign. ($p \leq 0.05$)	S (Gc+Rw)	S (Rw)/ S(Gc+Rw)	S/ S(Gc+Rw)	R–Sq (Gc+Rw) (adj)	R–Sq (Rw) (adj)	R–Sq (adj)
Rw $= 6.45 + 6.19\ \log GcP - 1.59\ \log Aca$	Con, logGcP, logAca	1.1	-	1.4	0.59	-	0.16
D $= 0.611 - 0.0631\ \log Aap + 0.0477\ \log GcD - 0.148\ \log Rw$	Con, logAap, logGcD, logRw	0.043	1.1	1.8	0.72	0.69	0.10
Cl $= -2.33 + 1.28\ \log Aca + 2.03\ \log Aap + 0.00320\ GcD^2$	Con, logAca, logAap, GcD^2	0.25	1.1	1.1	0.80	0.77	0.74
Cd $= 26.0 + 0.102\ Aca^2 + 1.50\ \log Aap - 5.17\ GcP$	Con, Aca, GcP^2	2.0	1.1	1.1	0.43	0.33	0.25
CWT $= 2.91 + 0.761\ \log Aca + 0.347\ \log Aap + 0.0531\ Rw - 1.08\ GcP^2$	Con, logAca, logAap, GcP^2	0.29	1.1	1.2	0.48	0.33	0.28
Lw $= -0.442 + 0.170\ \log Aca + 0.252\ \log Aap - 0.110\ \log Rw + 0.0124\ GcD$	Con, logAca, logAap, logRw, GcD	0.054	1.2	1.6	0.79	0.72	0.46
Mfa $= 69.5 - 11.3\ \log Aca - 27.2\ \log Aap + 3.42\ \log Rw - 0.0871\ GcD^2$	Con, logAca, logAap, logRw, GcD^2	3.7	1.3	1.5	0.79	0.66	0.52

Note: GcP, proportion green crown; GcD, distance to green crown; (Rw), information on Rw is added to data on Aca and Aap; (Gc+Rw), information on GcP or GcD (Gc) and Rw is added to data on Aca and Aap. For abbreviations and further information, see Table 2.

(for Brinell hardness at longitudinal direction) annual ring width. In sapwood at intermediate top height, the major contributor was density and (for Brinell hardness at tangential direction) annual ring width and microfibril angle. Differences in density and annual ring width and (for Brinell hardness at tangential direction) microfibril angle were the major reasons for the accentuated differences between the regimes in sapwood compared to heartwood and in heartwood at intermediate top height compared to heartwood at stump height.

The characteristics that made major contributions to the higher relative stiffness (i.e. less creep) in SDR (Fig. 6) were cell morphological characteristics and the proportion of latewood in all sub groups. These characteristics were also the major reasons for the variations in the magnitude of differences in different sub groups between the regimes.

3.3 Prediction of Wood Structure Characteristics

The best models for predicting wood structure characteristics – which included green crown, ring and age parameters – had r^2 values of ~0.8 for cell length, microfibril angle and proportion of latewood, more than 0.7 for density, almost 0.6 for annual ring width, almost 0.5 for cell wall thickness and higher than 0.4 for cell width (Table 6). Excluding green crown parameters from the best models increased the standard deviation by almost 45 % for annual ring width, more than 25% for microfibril angle, about 15% for proportion of latewood and cell wall thickness, almost 10% for cell diameter and length, and more than 5% for density. Differences in the increase of standard deviation between models in which both green crown parameters and annual ring width were excluded and models in which only green crown parameters were excluded, indicate the contribution of annual ring width to the increase in predictive capacity. According to this criterion, the contribution of annual ring width to the increase in predictive capacity was ~75% for density, ~45% for proportion of latewood, ~25% for microfibril angle, and close to zero for cell morphological parameters.

4 Discussion

4.1 Material and Methods

The study was designed to compare two groups of trees with contrasting silvicultural background, i.e. the focus was more on trees and regimes than on stands. To characterise wood from a material scientist's perspective clear wood, without structural defects like spiral grain and resin pockets, were studied due to its homogenous properties and many of the used variables are similar to parameters included in steel norms and plastic datasheets. As a consequence of the laborious analyses, the number of trees was restricted. However, since the variation between trees within regimes was relatively small within subgroups, see Figs. 7 and 8, and because two contrasting silvicultural regimes were compared, the potential of regimes as a tool to regulate wood structural characteristics and mechanical properties is shown. Further support for that the tree-to-tree variation within the regimes was much smaller than the differences between the regimes, is the fact that the differences between the regimes were significant both for mechanical properties (Table 5) and structural characteristics (Table 3).

One feature of the PWR trees was that the ring width increased with increased cambial age at stump height due to the release thinning (spacing of 10m) at an age of nine years. As a consequence, the crown was constantly growing bigger after the first nine years and the ring width was increasing. Another feature of the PWR trees was that close to the bark, as opposite to close to pith, annual rings were wider at stump height than at intermediate top height, which probably is an effect of wind (related to crown size and the wide spacing).

It seems that it will take very long time (if ever) until the PWR trees will produce strong wood. The SDR trees produce strong wood after the first 20 years from the pith. The reason for the difference is that SDR trees have produced mature wood, while PWR trees have not, see Table 3 and Fig. 2. The comparison was made up to a cambial age of 42 years as wood with higher cambial age than 42 years probably have similar properties, for the respective regimes. As PWR trees did not produce mature wood, only differences between heartwood and sapwood in juvenile wood could be studied in different radial positions.

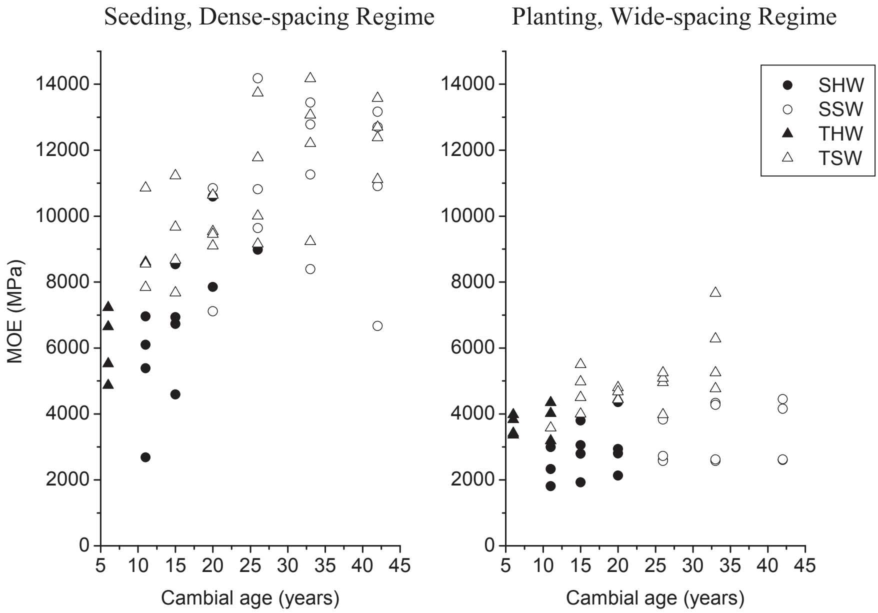

Fig. 7. Differences in stiffness between SD- and PW-regimes in relation to cambial age in heartwood (…HW) and sapwood (…SW) at stump (S…) and intermediate top (T…) heights in the trees.

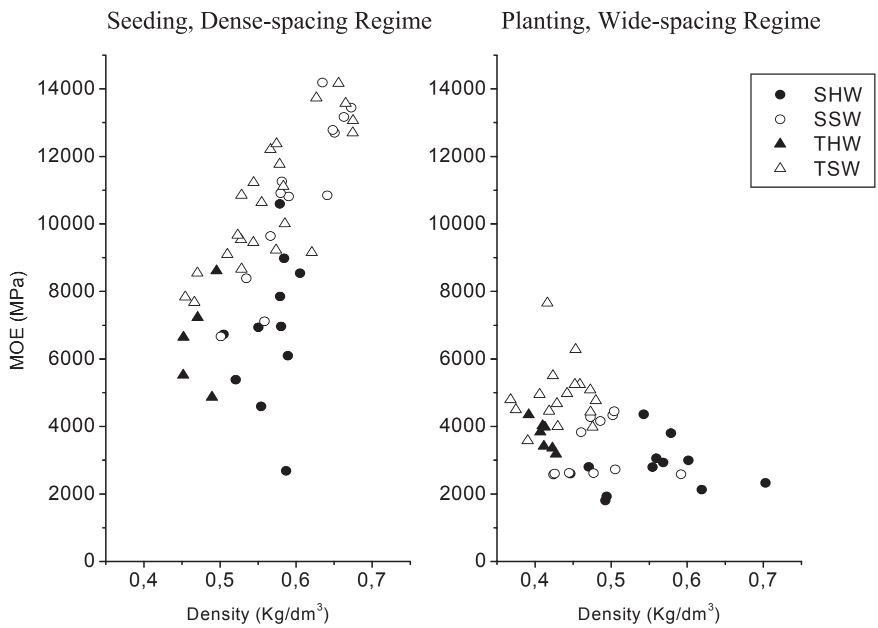

Fig. 8. Differences in stiffness between SD- and PW-regimes in relation to density in heartwood (…HW) and sapwood (…SW) at stump (S…) and intermediate top (T…) heights in the trees

When comparing different wood tissue types it is important to note that the heartwood in general is more juvenile than the sapwood, since its cambial age is younger (Kyrkjeeide 1990, Table 2). Comparisons between the regimes may also be influenced by differences in the vertical positions sampled in the trees, i.e., by the age of the apical meristem (Olesen 1982, Groom et al. 2002, Mattsson 2002,) and cambial age (Kyrkjeeide 1990, Mencuccini et al. 1997, Bruchert 2000). However, contributions of differences in age to differences in mechanical properties were minor except for some effects in heartwood at intermediate top height (Figs. 1–6).

High r^2 values in the predictive equations indicate that the methods used in the tests of mechanical properties and structural characteristics are accurate. In addition, the similarity of values for calculated and observed differences and the high r^2 values in the predictive equations provide indications that the equations are appropriate. Calculated differences in compression strength between the regimes deviated more from observed differences when each cell morphological characteristics is separated in the calculation compared to when total sum is used. Therefore sum of cell morphological characteristics were used in subsequent analyses. Finally, the r^2 values (and thus the predictive capacity) of equations linking green crown, ring and age parameters with cell length, microfibril angle, proportion of latewood, density and annual ring width are quite high (~0.6 to 0.8), indicating that the methods applied are appropriate.

4.2 Comparison and Prediction of Structural Characteristics

The large differences in green crown parameters between the regimes are probably mainly due to differences in stand stem density (cf. Lindström 1996, Groom et al. 2002). The results show that green crown parameters have a strong effect on annual ring width, which (in turn) strongly influences the density of the wood. Predictions of proportion of latewood and microfibril angle imply that differences between the regimes are due to the influence of both annual ring width and green crown properties on maturation of the cambial meristem (Persson 2000, Groom et al. 2002). The developed functions also imply that differences in cell morphological parameters are due to variations in green crown properties, but not annual ring width, via their effects on the vascular cambium (Groom et al. 2002), although to a lesser degree than the other characteristics. Results indicate that differences in both annual ring width and green crown parameters between regimes are the likely reasons for the faster maturation of the vascular cambium with cambial age in SDR than in PWR (Zobel and Buijtenen 1989, Mattsson 2002). A possible explanation for the weaker differences in the proportion of latewood and cell morphological characteristics higher in the trees than at stump height is that influences of green crown, ring and age parameters on the vascular cambium may be additive up to a maximum level, which is probably only reached by the samples from SDR at intermediate top height in trees. Finally, correlations between green crown proportion and wood structural characteristics have also been found by Amorasekara and Denne (2002). However, together with age parameters, green crown parameters and annual ring width can, both in combination and separately, provide accurate predictions regarding characteristics of wood samples from the two tested regimes at different ages of the rotation period.

4.3 Mechanical Properties

Structural characteristics of wood strongly influence its mechanical properties. The fact that differences between the regimes in stiffness and strength are greater than differences in hardness and creep are probably related to differences in the proportions of juvenile wood associated with the regimes and the high correlation between juvenility and stiffness (El-Hosseiny and Page 1975, Bendtsen and Senft 1986, Hunt 1999, Holmberg 2000). The small differences found in creep between SDR and PWR may also be due to the use of short creeping times (cf. Hunt 1999). The large differences between the regimes and the subgroups in stiffness and the relationships between density and stiffness (Fig. 8) highlight the strength of the influence of the silvicultural regime and wood tissue type even when the difference in density is relatively small.

Effects of annual ring width on mechanical properties are strongly analogous to effects of density (Dinwoodie 2000). Consequently, effects of annual ring width are probably indirect effects of density. The negative effect of small microfibril angle on bending strength in heartwood is probably due to a negative effect of heartwood formation on wood with small microfibril angles in earlywood cells, since there is a negative effect of low mean microfibril angle, and a positive correlation between bending strength and wood with low microfibril angles in latewood cells. Furthermore, in contrast to the situation in sapwood, the proportion of latewood is an important characteristic in heartwood.

The fact that density explains most of the difference in hardness between the regimes is in accordance with Holmberg (2000). The apparent negative effect of small microfibril angle on Brinell hardness at longitudinal direction in heartwood at stump height is probably due to a negative effect of heartwood formation on wood with small microfibril angle in earlywood cells, for similar reasons to those noted above concerning bending strength.

Results on plasticity and viscosity of single tracheid cells presented by Groom et al. (2002) may explain the importance of cell morphological characteristics and proportion of latewood in creep. The apparent negative effects of high apical meristem age and density on creep are probably due to covariance with variables that are important, but were not measured.

4.4 Conclusions

Clearly, wood samples from stands subjected to two contrasting silvicultural regimes can differ greatly, both in structural characteristics (here up to fivefold for means of all samples) and mechanical properties (here up to almost threefold for means of all samples). Furthermore, tree-to-tree variation within subgroups is much smaller within regimes than the differences between regimes. It also seems that structural characteristics can be ranked, in order of their proportional differences (high to low) in trees from a regime involving seeding and dense spacing and from a regime involving planting and wide spacing as follows: late wood proportion, distance to green crown, annual ring width, proportion of green crown, microfibril angle, cell length, density, cell wall thickness and cell diameter. Mechanical properties are also clearly affected by the silvicultural regime. As demonstrated here, the difference between regimes in means of different properties for all samples can vary from a few percent (creep) up to almost threefold (stiffness). The rankings for mechanical properties in terms of their proportional differences between the regimes (high to low) are: stiffness, bending strength, compression strength, Brinell hardness at tangential direction, Brinell hardness at longitudinal direction and creep (for which little or no difference was found). The rankings can be explained by differences in the sensitivity of the properties to maturation of wood characteristics. Maturation of characteristics related to cambial age seems faster in a regime with dense spacing and differences are weaker at intermediate top heights in trees than at stump level. Consequently, for stiffness and strength properties the rankings for the magnitude of differences between the regimes are very similar in the different sub sample groups, as are the structural characteristics. For hardness properties the rankings are almost the same, but the differences between the regimes are greater in heartwood at intermediate top height than at stump height. The greatest observed differences in ranking and magnitude of differences between sub groups of samples were related to creep: the greatest differences occurring in sapwood at stump height, then heartwood at stump and intermediate top heights and lowest in sapwood at intermediate top height. Furthermore, the number of wood characteristics that make major contributions to differences, between silvicultural regimes or sub groups, should be highest for stiffness, then strength and hardness properties, and lowest for creep. Using green crown properties, annual ring width and age parameters, it seems possible to predict wood structural characteristics and mechanical properties for different parts of the rotation age. Also, the scope for using the silvicultural regime to regulate wood structural characteristics and mechanical properties is high. A silvicultural regime could therefore be seen as a tool to select material qualities and to make wood a more homogenous material for engineering.

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