Variations in Basic Density, Shrinkage and Shrinkage Anisotropy of Scots Pine Wood from Mature Mineral Soil Stands in Finland and Sweden

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Abstract

Variations in basic density, radial and tangential shrinkage, and shrinkage anisotropy of wood in mature Scots pine trees growing on mineral soil stands were studied based on empirical materials from five geographical regions in Finland and Sweden. Cambium age explained better the pith-to-bark variation in basic density, as well as in tangential and radial shrinkage, than the distance from the pith. The model for radial density variation was evaluated on a cross-sectional scale; it explained approximately 50% of the density variation of the cross-sections. Based on the mixed model analysis with repeated measurements structure, approximately 52% of the variation in basic density on a cross-sectional scale was explained by the geographical origin and height position within a tree. By adding variables describing the trees and stands more precisely, approximately 64% of the total variation within trees and between trees, stands, and regions could be explained. In both cases, within-tree and between-tree random variation was statistically significant. The geographical origin affected significantly the variability in the studied properties; especially the within-tree variations decreased from the south to the north. On the other hand, the average level of radial and tangential shrinkage, as well as basic density, was the lowest in the north.

Key words: *Pinus sylvestris,* Scots pine, wood quality, basic density, shrinkage, linear mixed model, repeated measures

Introduction

Basic density affects significantly a variety of other physical properties of wood. Especially, variability in mechanical properties of clear wood can mainly be attributed to slope of grain and wood density (Kollmann and Côté 1968, Dinwoodie 1975, Bodig and Jayne 1982). Moreover, strength and stiffness, particularly along the grain, decisively depend on density (Haller 2007).

Basic density of Scots pine (*Pinus sylvestris* L.) wood from the very northern latitudes is significantly lower compared to the wood with a more southerly origin (e.g., Hakkila 1979, Kellomäki 1979, Andersson 1983, Björklund and Walfridsson 1993). In addition, the density increases from the pith to the bark, and decreases from the butt towards the top of the tree (e.g., Tamminen 1962, Hakkila 1966, Uusvaara 1974).

As the basic density affects significantly the shrinkage of wood - the shrinkage being generally lower, the lower the density - the shrinkage mainly follows similar pith-to-bark patterns as basic density. Concerning the practical applications, severe variations in tangential or radial shrinkage within pieces of sawn timber, for example, cause remarkable stress gradients and, thus, increase the possibility of deformation and cracking during drying and in varying end use conditions. In addition, the inequality of radial and tangential shrinkage (shrinkage anisotropy), and especially the pith-to-bark variation in shrinkage anisotropy connives in emergence of cracks and deformations. The same basic principles of variation-caused gradients mainly apply also to the basic density.

In this study, the principal aim was to map out the levels of and variations in basic density of wood in mature Scots pine trees growing on mineral soil stands in five regions ranging from northern Finland to southern Sweden. On the one hand, pith-to-bark variations were studied by means of nonlinear regression analysis; on the other, mixed model analyses were executed to study more thoroughly the density variations and factors affecting the density at different hierarchical levels. In addition, the functions describing pith-to-bark basic density variations were evaluated against density measurements from sectors of clear wood. Principally, the models constructed were not intended for prediction of the studied properties based on the background variables. The secondary aim of the study was to investigate the variations in radial and tangential shrinkage and shrinkage anisotropy of wood and the factors affecting these properties.

Materials and methods

Empirical materials

Tree, log, and wood samples from sixty mature Scots pine dominated stands growing on mineral soils were collected in three regions in Finland (northern, southeastern, and central inland) and two regions in Sweden (south-central and southern), 12 stands from each (Fig. 1), to cover the geographical spread for latitude and altitude, accordingly, the climate for effective temperature sum. For the sake of clarity in the statistical analyses, the regions were numbered in ascending order starting from the northernmost region (northern Finland=region 1 … southern Sweden=region 5). In each region, the stands were selected randomly to represent different forest sites and age classes of mature stands. In Finland, the sampling was based on the sample plot network of the 8th (in the north) and 9th (in the south) National Forest Inventory (NFI); in Sweden, on the records of the landowner, Sveaskog Ltd. In each stand, three Scots pine trees covering the diameter range of conventional saw log and small-diameter log trees (DBH>14cm) were felled for sampling, the total sample being 180 trees. At first, a circular experimental plot was randomly placed on each stand, which after the DBH of each Scots pine tree on the plot was measured. The averaged values from two measurements perpendicular to each other were used. Then, separately on each plot (stand), all the trees with the DBH exceeding 14cm were put in ascending order based on the DBH, and the sample trees were evenly selected from the DBH series. More detailed descriptions of regions and sample trees are given in Tables 1 and 2.

From each sample tree, 70-cm bolts were cut from the sections of butt log, middle log, and top log (at 2, 6, and 10m heights, respectively). Based on the average tree heights, the bolts from 10m height were considered to represent the top log section of the trees in the most northerly region. The same definition for the top logs was then used in all regions, respectively. From the top of each bolt, a disc with the thickness of 30mm was sawn. In the northernmost region, the minimum sample tree height was only 10.1m; thus, a total of 531 discs from the exact heights of 2.7, 6.7, and 10.7m were obtained. From each disc, one to three

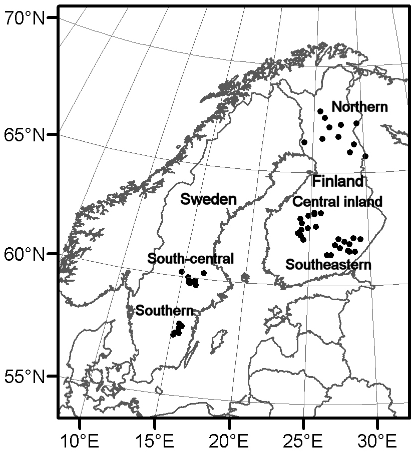

Figure 1. Location of the 60 stands sampled in five regions in Finland and Sweden. Map: Nivala V. and Lukkarinen A., Metla

Table 1. Basic climatic characteristics of sample plots in different regions. N/A=no information available

	Elevation, m			Effective temperature sum, dd			Annual precipitation sum, mm		
Region	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
1 NF	215	130	280	816	714	923	515	475	565
2 CIF	160	110	205	1102	1031	1194	575	535	605
3 SEF	110	85	125	1227	1175	1285	595	590	605
4 SCS	130	80	200	1233	1163	1282	N/A	N/A	N/A
5 SS	170	145	190	1313	1293	1329	N/A	N/A	N/A

Table 2. Basic description of sample trees in different regions

	DBH over bark, cm			Height, m			Lower limit of live crown, m			Age, years		
Region	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
1 NF	23.8	15.0	31.1	16.5	10.1	22.2	9.6	4.3	17.0	173	67	295
2 CIF	28.7	18.7	41.4	22.5	15.8	29.3	14.1	6.7	19.3	129	94	178
3 SEF	28.7	17.1	42.6	23.5	16.4	29.8	14.0	5.4	19.0	97	61	155
4 SCS	29.4	18.0	39.9	22.6	16.5	30.0	13.4	8.1	19.3	108	90	130
5 SS	32.3	20.5	42.9	23.7	16.0	33.1	14.7	7.4	23.5	124	73	178

clear wood specimens with the dimensions of 20*20*30mm (radial*tangential*longitudinal) were cut along the north-south measurement line at different locations with relation to the pith, from both heartwood and sapwood (wood specimens A, N=2,301). In addition, sectors of clear wood were sawn (wood specimens B, N=496); the central angle of the sectors ranged from 16° to 44°.

For wood specimens A, the radial location in the cross-section of tree was determined using two approaches: 1) the number of annual rings (cambium age), 2) the exact distance (in mm), both from the pith to the centre point of the specimens. The unextracted basic density (kg/m^3), radial and tangential shrinkage from green to oven-dry condition, and the average ring widths were determined according to Kučera (1992). The value describing shrinkage anisotropy was calculated as a ratio between tangential and radial shrinkage in a specimen. For wood specimens B, the basic density (kg/m^3) of the sectors without bark was determined imitating the procedure for small clear specimens (Kučera 1992), and this density was used to describe the basic density of the entire-cross section. Circular cross-sections were assumed. In each sector, the latewood proportion of each annual ring was calculated according to the definition of Mork (1928) and the results were averaged to the cross-sectional level. In the literature, two interpretations of the Mork's formula has been commonly used (Denne 1988). In this study, all tracheids with the double cell wall thickness equal to or greater than the lumen diameter in radial direction were assigned to the latewood.

Statistical analysis

Basic density

The variation in basic density within a cross-section, that is, from pith to bark, was studied using the results on wood specimens A. The dependence of basic density on cambium maturity was modelled by fitting an exponential equation to the data (Kärenlampi and Riekkinen 2004):

$$r = r_0 + \Delta_r \left[1 - \exp(ax)\right]$$

where r is the basic density (kg/m^3) at given maturity, r_0, Δ_r , and a are constants, and x is the applied measure of cambium maturity (cambium age or distance from the pith). Eq. 1 was fitted separately to the data of each region and at each height position within a tree.

Eq. 1 does not take into consideration the possible combined effect of cambium maturity and distance from the pith on the basic density. To study the possible presence of the interaction effect, Eq. 1 was reformulated as follows (Kärenlampi and Riekkinen 2004):

$$r = r_0 + \Delta_r \left\{1 - \exp\left[\bar{a}\left(\bar{x}_{age}{}^{m}\,\bar{x}_{DFP}{}^{1-m}\right)\right]\right\}$$

where $\bar{a}$ is constant, $\bar{x}_{age}$ and $\bar{x}_{DFP}$ are the above-discussed cambium maturity parameters made dimensionless by normalising with their arithmetic mean values, and is a scaling factor ranging from 0 to 1. When $m = 0$, only the distance from the pith is an independent variable, whereas the cambium age is the only independent variable in the equation when $m = 1$. An interaction effect of these independents is present when $0 < m < 1$ (Kärenlampi and Riekkinen 2004).

To study the variations in basic density within trees (from butt to top) and between trees, plots, and regions, data measured from wood specimens B were used. Simple one-way ANOVA were executed to compare the average densities in the different regions and at different height positions within a tree, and pairwise LSD comparisons were performed to find out the significant differences between individual regions and heights. In addition, the variations in basic density were studied more exhaustively by means of linear mixed model analyses. With these models, the dependence of basic density on the selected background variables was determined, while accounting appropriately for the hierarchical structure with region, stand, tree, and within-tree levels. The general structure of the mixed model was

$$y = \mathbf{Xa} + \mathbf{Zb} + \mathbf{e}$$

where **a** and **b** are the vectors of fixed and random parameters, **X** and **Z** are the respective model matrices, and **e** is the vector of errors.

Two basic types of mixed models were formulated to describe the variation in the cross-sections' basic density. In the type A model, only readily available fixed factors, that is, region and height position within a tree were included, whereas, in the type B model, a full range of available background variables were considered as independent factors. In the type B model, the fixed covariates included were centred around their universal averages. Maximum likelihood (ML) based likelihood ratio tests (LRT's) were executed to choose the fixed parameters to be included into the model and to detect a model with the best possible fit. LRT's were constructed by subtracting the values of -2 log likelihood for two nested models and comparing this value against the distribution with degrees of freedom equal to the difference in the number of model parameters (Wolfinger 1996).

In both model types, the height position within a tree was considered as a longitudinal (correlated or repeated) variable with tree nested within stand and within region as a subject. The covariance structures of diagonal (DIAG), first order autoregressive (AR1), and heterogeneous first-order autoregressive (ARH1) were considered (Wolfinger 1996, Anon. 2005). In addition, a non-repeated model structure was considered. To find out the best covariance structures for random and repeated factors, Akaike's Information Criterion (AIC) was used (Akaike 1973). In addition, restricted maximum likelihood (REML) based likelihood ratio tests (RLRT's) were used to select between the covariance structures; the procedure was identical to that with LRT's, but the likelihood ratios were calculated based on -2 restricted log likelihood values.

To ensure the fit of the models, the residuals were examined as a function of predicted values and the normal distribution of residuals was checked. Coefficients of determination were calculated by squaring the correlation coefficients between the measured and fixed predicted values. The statistical analyses were conducted with the SPSS for Windows 14.0 software.

Shrinkage and shrinkage anisotropy

The dependence of tangential and radial shrinkage on cambium maturity was studied by fitting Eq. 1 to the data. In addition, the pith-to-bark variations in shrinkage anisotropy values were studied by fitting simple power equations to the data separately for each region and height position within a tree. Due to the biased values of tangential shrinkage owing to the geometry of the used specimens, only the dependence of radial shrinkage on a variety of background variables was studied more exhaustively by mixed model analysis (Eq. 3). The general structure of the model and the procedure of the analysis were as described in the previous section with an exception that only non-repeated model structure was considered.

Results

Basic density

Variation from pith to bark (wood specimens A)

In general, the basic density of wood increased from the pith outwards in all regions and log types. Only in the top logs from northern Finland the density, rather linearly, decreased from the pith to bark. Cambium age (age), generally, explained better the radial variation in density than did the distance from the pith (size); higher coefficients of determination and lower standard errors of estimate were discovered for age as an independent variable (Eq. 1). The standard errors of estimate ranged from approximately 27kg/m³ to 40kg/m³ in models with the age and from 26 kg/m³ to 49kg/m³ with the size as the independent variable, respectively. In the top logs from northern Finland, the decrease in density with increasing maturity caused anomalous parameter estimates of Eq. 1 (Table 3).

The effect of cambium maturity on basic density was generally the strongest in the butt and the weakest in the top logs. In the butt logs, approximately 34% to 63% of the density variation could be explained by cambium age and 17% to 44% by the distance from the pith in the different regions, whereas, in the top logs, the respective values ranged from 10% to 20% with the age and from 6% to 20% with the size as an independent variable. In the middle logs, the coefficients of determination were relatively close to the values in butt logs in all regions excluding northern Finland, where rather dramatic decrease in the coefficient of determination was explored. The explanatory

		Independent variable *age*					Independent variable *DFP*				
Height m	Region	r_o kg/m³	Δ_r kg/m³	a year^{-1}	R² %	SEE kg/m³	r_o kg/m³	Δ_r kg/m³	a mm^{-1}	R² %	SEE kg/m³
2.7	1 NF	346	96	-.053	34	31.6	339	99	-.047	17	35.6
	2 CIF	293	187	-.078	56	36.1	294	193	-.033	44	41.0
	3 SEF	227	260	-.148	63	38.7	321	182	-.027	41	48.6
	4 SCS	262	220	-.158	53	40.2	219	263	-.058	36	46.7
	5 SS	272	224	-.134	62	34.1	194	301	-.063	38	43.6
6.7	1 NF	356	43	-.088	8	31.9	357	41	-.055	3	32.8
	2 CIF	320	114	-.087	47	30.4	323	127	-.023	40	32.3
	3 SEF	311	146	-.104	55	33.8	303	158	-.033	39	39.7
	4 SCS	165	273	-.355	36	33.5	211	228	-.084	23	36.8
	5 SS	293	160	-.142	48	32.7	231	224	-.058	39	35.1
10.7	1 NF	389	-26943	-7.8E-6	10	26.9	398	-3929	-1.1E-4	14	26.4
	2 CIF	359	54	-.094	17	29.6	376	285	-.002	20	29.0
	3 SEF	197	225	-.356	20	36.7	235	186	-.092	11	38.7
	4 SCS	237	180	-.325	17	32.3	370	49	-.044	6	34.3
	5 SS	339	81	-.166	20	27.3	329	92	-.062	17	27.8

Table 3. Parameter estimates of Eq. 1 describing the variation in basic density when using cambium age (age) or distance from the pith (DFP) as an independent variable. The equation was fitted separately for the different heights and regions. R²=coefficient of determination, SEE=standard error of estimate

power of cambium maturity was the weakest in northern Finland; however, the standard errors of estimate were also the lowest in the north (Table 3).

The differences in the relationships between cambium maturity (age or size) and basic density can be studied by comparing the parameter estimates of Eq. 1 fitted to the data separately for each height and region. Here,   describes the level of average basic density in the vicinity of the pith, whereas   delineates the average density difference between the inner and outer parts of the cross-section (Fig. 2). In addition,   determines the shape of the average density curve; the higher the absolute value is, the more abrupt the slope of the maturity-density curve (Figure 3a). In this respect, the wood density seemed to be more homogeneous within cross-section in northern Finland than in other regions in this study. In addition, the density homogeneity seemed to increase towards the top of the tree (Table 3). Compared to the age, significantly lower gradients of maturity-density curves were observed with the size as an independent variable (Table 3, Figs. 3a and 3b).

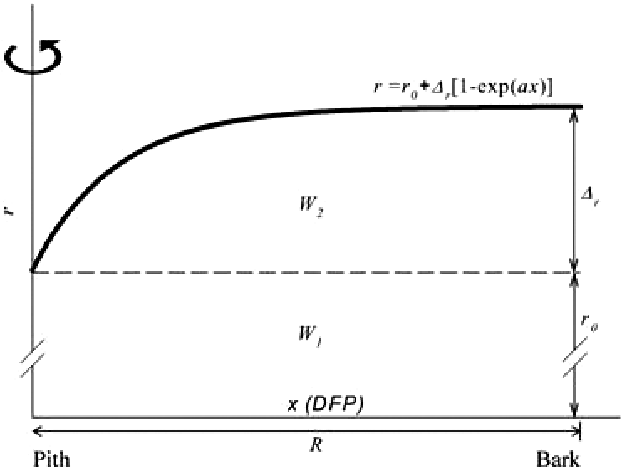

Figure 2. Illustration of maturity-density equation (Eq. 1) and formation of the solid of revolution (Eqs. 8 and 9)

Considering the possible combined effect of cambium age and size (Eq. 2), in most of the cases, the age alone was the best predictor of basic density along the radius of the stem (m = 1). Only in the top logs from northern Finland the DFP alone explained better the variation in basic density than the age (m = 0). A significant combined effect of age and size was found in the top logs from central inland Finland (m = 0.047), as well as in the middle logs (m = 0.829) and top logs (m = 0.775) from southern Sweden. In practice, the improvements achieved by the inclusion of the combined effects were only marginal in the prediction; the decrease in the residual sum of squares ranged from 0.03% to 0.22%, and the coefficients of determination and standard errors of estimate were practically identical to the ones obtained using Eq. 1 with the size in the first case and the age in the two latter cases as the explanatory variable.

Variation in cross-sectional scale (wood specimens B)

Region affected significantly the basic density of the-cross sections (one-way ANOVA: df=495, F=21.037, p<0.001). The density clearly increased from the north to the south in this study (Fig. 4), and significant differences were found between all regions, with the exceptions of southeastern Finland and both south-central and southern Sweden. The height position within a tree also affected the basic density (one-way ANOVA: df=495, F=140.655, p<0.001) and the average densities at the three height positions differed significantly from each other. In each region, the basic density was at a significantly lower level in the middle logs compared to the butt logs, as well as in the top logs compared to the middle logs, respectively. In the butt logs, the basic density of wood from northern and central inland Finland, as well as from southeastern Finland and south-central Sweden, did not differ significantly from each other. In the middle and top logs, respectively, no significant differences were found between any of the three most southerly regions (Fig. 4).

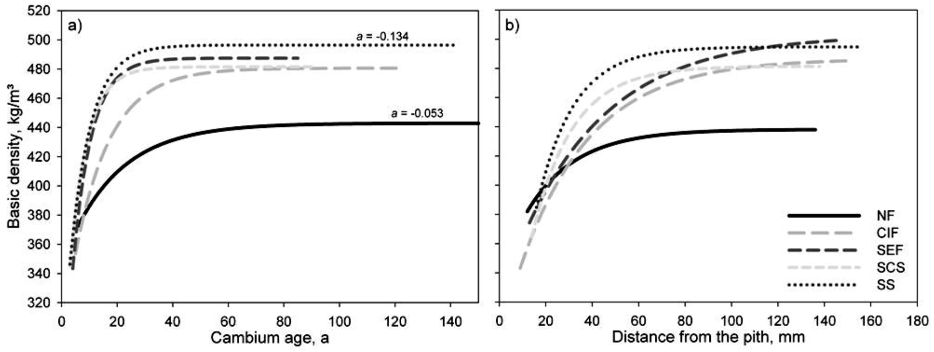

Figure 3. Average curves (Eq. 1) for basic density as a function of cambium age (a) and distance from the pith (b) in butt logs in different regions. The interpretation of parameter   of Eq. 1 is also shown

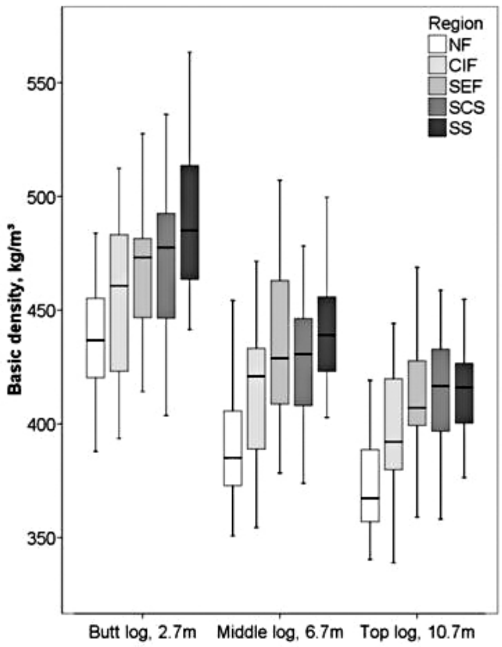

Figure 4. Box and whiskers plots of cross-sections' basic density in butt, middle, and top logs in different regions

The following mixed models were found to best explain the variation in basic density:

Type A Model:

$$r_{ijkl} = b_0 + \sum_{l=1}^{5} b_{1l}\, reg_l + \sum_{i=1}^{3} b_{2i}\, hgt_i + u_{0jkl} + e_{ijkl}$$

Type B Model:

$$r_{ijkl} = c_0 + c_1 tsum_{kl} + c_2 lwprop_{ijkl} + \sum_{i=1}^{3} c_{3i} hgt_i + c_4 rate_{jkl} + c_5 relhgt_{ijkl} + u_{0jkl} + e_{ijkl}$$

where r_{ijkl} is the basic density (kg/m³) at position i (i = 1butt, 2 middle, 3 top log) in tree j in stand k in region l (l = 1 NF, …, 5 SS). In addition, b and c are the estimates for the fixed effects, reg_l and $hght_i$ are dummy variables for region and height position within a tree, $tsum_{kl}$ is the effective temperature sum (dd), $lwprop_{ijkl}$ is the average latewood proportion in a cross-section, and $relhgt_{ijkl}$ is the relative height position within a tree. Moreover, $rate_{jkl}$ is a measure for average diameter growth rate (mm/a) calculated by dividing the tree DBH (over bark) by the tree age at stump height. The average values and ranges of the tree and position level model covariates are given in Table 4. The tree level random effect was denoted by $u_{0jkl} \sim N\left(0, \sigma_{u0}^2\right)$, and the residual term by $e_{ijkl} \sim N\left(0, \sigma_{e0}^2\right)$. Within-tree, stand, and region level random effects were insignificant and, thus, not included into the models. Judging from AIC's and RLRT's, the ARH1 was found to best delineate the covariance structure of repeated effect of height position within a tree in both mixed models, hence the variances and covariances of the residual term were

$$Var(e_{ijkl}) = \sigma_{ei}^2$$

$$Cov(e_{ijkl}, e_{i'jkl}) = \rho^{|i-i'|}\sigma_{ei}\sigma_{ei'} \text{ if } i \neq i'$$

Table 4. Averages and minimum and maximum values of position and tree level model covariates in the type B mixed model in different regions (Eq. 5)

	$lwprop_{ijkl}$			$rate_{jkl}$			$relhgt_{ijkl}$		
Region	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
1 NF	.23	.13	.35	1.53	.70	3.07	.35	.09	.76
2 CIF	.22	.15	.31	2.49	1.17	4.27	.27	.07	.63
3 SEF	.24	.16	.32	3.00	1.68	4.27	.26	.07	.59
4 SCS	.21	.12	.29	2.73	1.62	4.04	.28	.07	.61
5 SS	.23	.12	.33	2.74	1.64	4.77	.27	.06	.63

In the type A model (Eq. 4), both fixed factors, region (F=19.999) and height position within a tree (F=597.279) were found to be statistically significant at the 0.001 level. The results agreed with the results of the above-discussed analyses of variances, as the density increased from the north to the south and decreased from the butt to the top. The estimates of fixed effect region in southeastern Finland and south-central Sweden, that is, b_{1_SEF} and b_{1_SCS}, did not differ from the estimate for southern Sweden (b_{1_SS}) at the 0.05 level, whereas b_{1_NF} and b_{1_CIF} differed from b_{1_SS} at the 0.001 level. On the other hand, the estimates $b_{2\_2.7m}$ and $b_{2\_6.7m}$ differed significantly from $b_{2\_10.7m}$ at the 0.001 level. Based on pair-wise comparisons, northern Finland differed significantly from the other regions at the 0.001 level; in addition, a significant difference in average density was found between central inland Finland and southern Sweden (p=0.001). The average densities in the butt, middle, and top logs clearly differed from each other (p<0.001). For the type A model, the coefficient of determination was 0.521 and the standard error of estimate 28.7kg/m³.

Compared to the type A model, the type B model (Eq. 5) explained a larger proportion of the basic density variation and also more precisely (R^2=0.637, SEE=25.0kg/m³). The effective temperature sum and, accordingly, the average latewood proportion had positive effects on the basic density, whereas the relative height position within a tree and the average growth rate affected negatively. The basic density decreased from the butt upwards and the estimates of $c_{3\_2.7m}$ and $c_{3\_10.7m}$ (Table 5), as well as the average densities in the butt and top logs differed from each

Table 5. Estimates and tests for significance of fixed parameters of the type B mixed model (Eq. 5). Estimate for $c_{3\_10.7m}$ was set to zero. SEE=standard error of estimate, Df=degrees of freedom, t=value of t-test, p=significance value

Parameter	Estimate	SEE	Df	t	p
c_0	420.5	4.017	255.6	104.7	<.001
c_1	.101	.012	179.7	8.363	<.001
c_2	313.4	39.81	374.4	7.873	<.001
$c_{3\_2.7m}$	27.43	7.32	253.9	3.747	<.001
$c_{3\_6.7m}$	4.441	3.871	290.6	1.147	.252
c_4	-7.376	2.623	183.3	-2.812	.005
c_5	-44.62	18.98	234.6	-2.351	.020

other at the 0.001 level. If the average latewood proportion was removed from the model the coefficient of determination was 0.540 and standard error of estimate 28.1kg/m³.

In both models, the residual terms were highly significant. In the top logs, the residuals contributed to approximately one-fourth to one-third of the total random variation, whereas, at the two other heights their magnitude ranged from 46% to 52%. In both models, the tree level random effect u_{0jkl} was significant at the 0.001 level accounting for 48% to 74% of the total random variance. The predicted ARH1 correlation coefficient ρ was 0.408 (p<0.001) and 0.217 (p=0.119) in the type A and B models, respectively.

The average basic density profile along the radius of the disc (Eq. 1) was used to estimate the basic density of the entire disc. At first, a solid of revolution was formed by rotating the area formed by the density profile curve (Eq. 1; $0 \le x \le R$, where R is the radius of the disc under bark) a full turn around the y axis (Fig. 2). The "volume" of the formed solid was divided into two parts; $W = W_1 + W_2$, where, assuming a circular cross-section of the revolution,

$$W_1 = \pi R^2 r_0$$

$$W_2 = 2\pi \int_0^R xr \, dx$$

Re-formulating from Eq. 1 and substituting into Eq. 9, W_2 can be expressed as

$$W_2 = 2\pi \Delta_r \int_0^R [x - x\exp(ax)] dx$$

The integral function in Eq. 10 can be solved by applying two sequential partial integrations. Finally, the predicted average density of the entire disc $\hat{r}$ can be calculated by dividing W by the surface area A, that is,

$$\hat{r} = \frac{W_1 + W_2}{A} = r_0 + \Delta_r \left\{ 1 - \frac{2[(aR-1)\exp(aR)+1]}{a^2 R^2} \right\}$$

where r_0, Δ_r, and a are constants acquired from Eq. 1. Here, $\hat{r}$ satisfactorily explained (R²=0.502, SEE=29.3kg/m³) the variation in the basic density of the discs when the predictions were based on the parameter estimates acquired separately for each region and height position within a tree (Table 3). By region, the coefficient of determination ranged from 0.311 in southeastern Finland (SEE=32.7kg/m³) to 0.510 in southern Sweden (SEE=27.3kg/m³) (Fig. 5a). Instead of regions, the parameters could also be estimated separately for each stand and height position within a tree. Then, the coefficient of determination was 0.614 and standard error of estimate 26.0kg/m³. By region, again, the coefficient of determination ranged from 0.463 in south-central to 0.643 in southern Sweden, whereas the

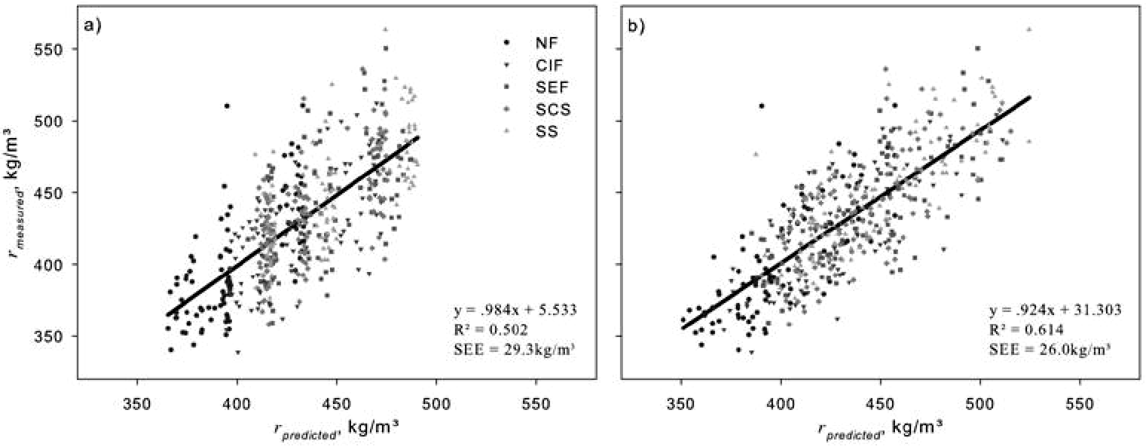

Figure 5. Measured basic density of the discs as a function of predicted values (Eq. 11); prediction was based on parameters separately for butt, middle, and top logs in each a) region and b) stand

standard error of estimate ranged from 23.5kg/m³ to 28.1kg/m³ in southern Sweden and southeastern Finland, respectively (Fig. 5b).

Shrinkage and shrinkage anisotropy

By region and height position within a tree, 35% to 70% of the variation in radial shrinkage of wood was explained by the Eq. (1) with the cambium age as the independent variable (Fig. 6). If the distance from the pith was used instead of cambium maturity, the respective coefficients of determination ranged from 0.23 to 0.60. Compared to the butt and middle logs, the coefficients of determination were at a clearly lower level in top logs. In addition, the lowest coefficients of determination were found in the northernmost region. Considering the tangential shrinkage, the coefficient of determination ranged from 0.06 to 0.48 and 0.25 to 0.51 with the cambium age or the distance from the pith as the independent variable, respectively. Again, the lowest coefficients of determination were found in the north in this study, whereas the differences in coefficients of determination between the butt, middle, and top logs were more or less inconsistent.

In all regions of this study, radial and tangential shrinkage decreased along the stem from the butt upwards. The shrinkage values seemed to be at a lower level in northern Finland compared to the other regions. In addition, the average patterns of shrinkage values from the pith outwards were the most homogeneous in the north, whereas, in this respect, no clear differences were found between the other four regions (Fig. 6). The ratio between tangential and radial shrinkage, that is, shrinkage anisotropy, clearly decreased from the pith outwards. On average, the anisotropy was at a lower level in the top logs than in butt and middle logs. In addition, the variation in shrinkage anisotropy, from pith to bark, was the lowest in the top logs and significantly increased towards the base of the tree. No significant differences were found in the levels of average anisotropy values between the regions, whereas, the radial variation in anisotropy was the lowest in the north (Fig. 7).

Based on the mixed model analysis, approximately 71 % of the variation in radial shrinkage could be explained by a wide variety of independent variables. In total, the model consisted of 38 parameters, of which 6 described random and 28 fixed effects, respectively. The shrinkage was affected most intensively by the basic density and selected combinations of density and other variables (Table 6).

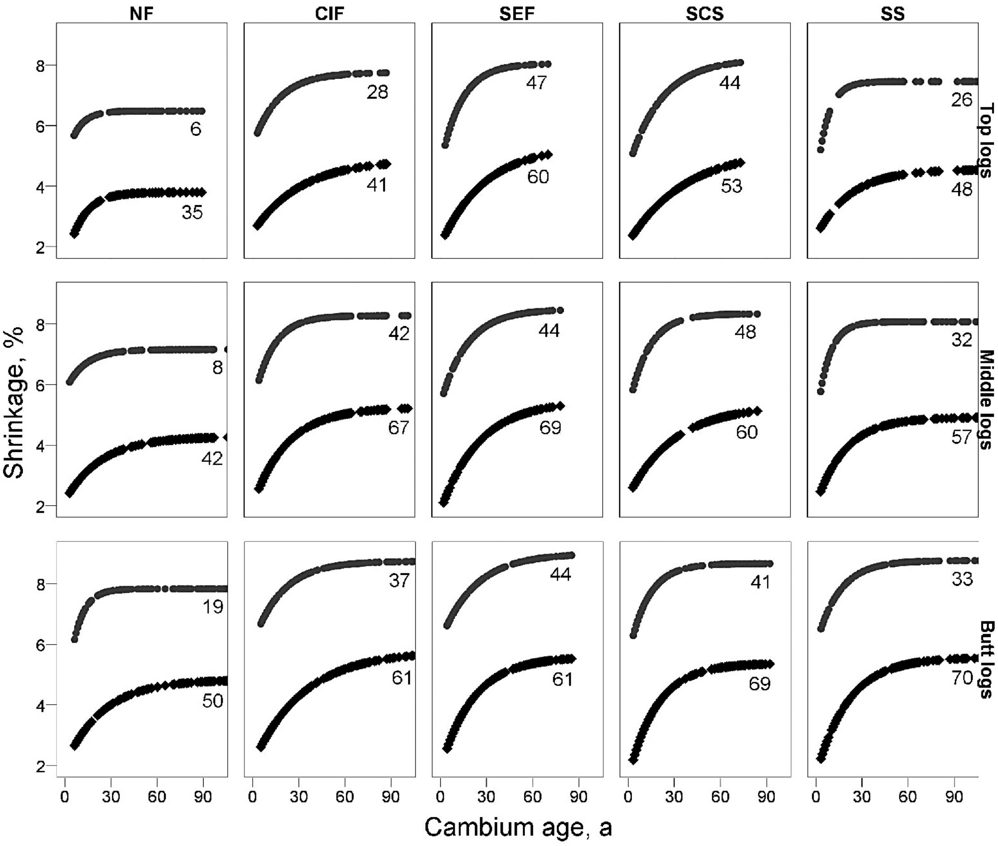

Figure 6. Average values of radial (black markers) and tangential (grey markers) shrinkage as a function of cambium age (Eq. 1) in different regions (columns) and height positions within a tree (rows). Coefficient of determination (%) for each case is shown. Figure is limited to the data for the first 100 rings from the pith

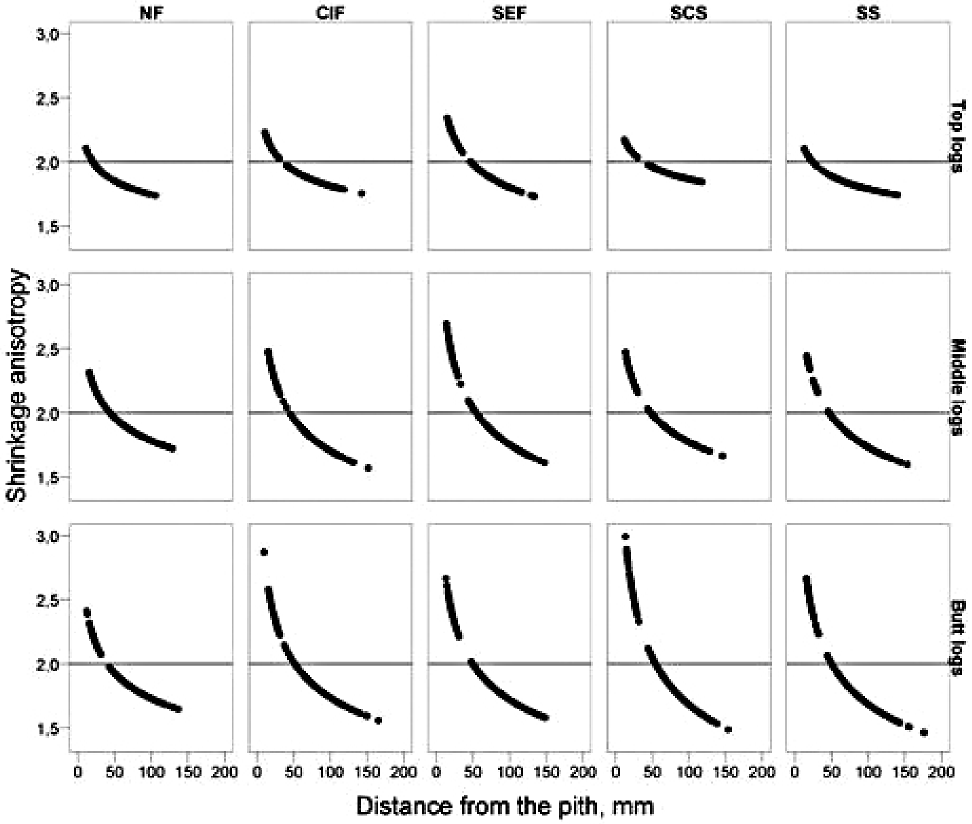

Figure 7. Average radial variation in shrinkage anisotropy in different regions (columns) and height positions within a tree (rows)

Table 6. Model dimension and tests of fixed and random effects for the mixed model describing the variation in radial shrinkage of small clear wood specimens. *Density*=basic density, *width*=average annual ring width, *age*=cambium age, *relhgt*=relative height position within a tree, *tempsum*=effective annual temperature sum, *DFP*=distance from the pith, *hgt*=height position within a tree, *reg*=region. *Test value*=value of *F* test for fixed effects and Wald *Z* test for random effects and residual, *p*=significance value

	Source	Subject variables	Test value	p
Fixed effects	Intercept		35.89	<.001
	Density^2		178.8	<.001
	*Density*Width*		159.2	<.001
	Density^3		139.7	<.001
	Age		91.12	<.001
	Relhgt		17.00	<.001
	Width		13.42	<.001
	*Width*Tempsum*		12.83	<.001
	*Density*DFP*		12.71	<.001
	Density^2*(Hgt)*		11.91	<.001
	*Age*DFP(Reg)*		11.01	<.001
	Reg		7.819	<.001
	Density^2*(Reg*Hgt)*		5.274	<.001
Random effects	*Age*	*Stand(Reg)*	2.911	.004
	Width	*Tree(Stand(Reg))*	3.440	.001
	Relhgt	*Tree(Stand(Reg))*	2.856	.004
	Density^3	*Tree(Stand(Reg))*	5.373	<.001
	Density^3	*Hgt(Tree(Stand(Reg)))*	2.745	.006
Residual			27.48	<.001

Discussion

It is well-known that basic density correlates significantly with annual ring width and latewood proportion of wood (e.g., Hakkila 1966, Nylinder 1967, Uusvaara 1974). On the other hand, ring width and latewood proportion are affected by cambium maturity (e.g., Sirén 1959, Dietrichson 1964, Hakkila 1966, Kärenlampi and Riekkinen 2004); therefore, the radial variation in basic density was analysed, here, only as a function of maturity itself. Basic density variation from pith outwards is a direct consequence of cambium maturation (Zobel and van Buijtenen 1989). In this study, the results clearly indicated that pith-to-bark variation could be better predicted by the cambium age (age) than the distance from the pith (size). In three cases out of 15, a significant combined effect of age and size was found, but, as the improvements achieved in the prediction were only marginal, the interaction effect of age and size could be ignored. These findings were in accordance with the results of Kärenlampi and Riekkinen (2004); they concluded for the butt sawlogs of Scots pine that cambium maturity and, thus basic density, was solely determined by age, not size. In earlier studies, approximately 35% to 45% of the radial variation in the basic density of Scots pine wood could be explained by cambium age (e.g., Hakkila 1966, Kärenlampi and Riekkinen 2004). In this study, slightly higher coefficients of determination were obtained for the butt logs and lower values for the top logs; the variation in basic density as a function of cambium maturity decreased from butt logs upwards and from the south to the north. Similar results were reported also in earlier studies by Hakkila (1966, 1968) and Björklund and Walfridsson (1993).

A general rule for Scots pine trees is the rapid increase in wood density from the low level in the juvenile wood zone, having then a short transition period, and followed by a levelling-off period towards the bark in the adult wood (mature wood). Over-mature trees frequently show a reduction in density near the bark (Zobel and van Buijtenen 1989). For Scots pine in southern Finland, decrease in basic density of over-mature wood (cambium age over 80–120 years) was reported at breast height (Velling 1974), as well as at stump height and at 60% and 70% relative stem heights (Hakkila 1966). Björklund and Walfridsson (1993) reported a clear radial decrease in the basic density of Scots pine wood at 50% relative stem height in northern Sweden. Also in this study, a rather linear decrease in basic density as a function of cambium maturity was observed in the top logs from northern Finland; then, the relative stem height ranged from 45% to 76%. As the basic density was determined unextracted, the effect of extractives increasing the density was larger in heartwood than in sapwood specimens, since the amount of extractives in Scots pine heartwood is approximately twofold compared to sapwood (Hakkila 1968). In heartwood, the highest amounts of extractives are found in the vicinity of the stump of the trees, whereas, in sapwood, the extractive content remains more or less constant along the stem (Kärkkäinen 1981); hence, the observed decrease in basic density from the pith outwards was due to other factors than the extractives.

With respect to Scots pine wood in Sweden, the first 10–15 rings from the pith could be considered as juvenile wood (e.g., Wilhelmsson et al. 2002). On the other hand, at 4m height in Scots pine trees from, for example, southwest Germany, the transition between juvenile and adult zone occurred, on average, at 22 rings from the pith, and the location of the transition did not vary between the stands (Sauter et al. 1999, Mutz et al. 2004). If this independence on geographical location were valid also in the very material, the amount of juvenile wood (in mm) would be the lowest in the north in this study due to narrower growth rings compared to origins that are more southern. Probably due to the size of the used specimens no evidence of density remaining constant or even decreasing in the radial section of the first 5–15 annual rings (e.g., Nylinder 1961, Velling 1974, Atmer and Thörnqvist 1982) was observed. In fact, the sparse distribution and the size of the used specimens prevented more accurate investigation of the maturation process and implication of juvenile wood in different regions.

As the number of annual rings decreases from the butt upwards, causing the proportion of juvenile wood to increase, the decrease in basic density at cross-sectional scale from the butt upwards is partly caused by the radial variation. Still, the average densities parallel to the pith differed significantly between the height positions within a tree (Table 3). The result indicated some functional changes in the cambium at different heights. This is probably controlled by the distance from the living crown of the tree, as the concentration of auxin and other hormones affecting the functions of the tissues of cambium decreases as the distance from the living crown increases (Hakkila 1966). On the other hand, the longitudinal differences may originate from the maturation of the apical meristem (Olesen 1978).

The results on radial, longitudinal, and geographical variations in basic density were in accordance with the earlier studies (e.g., Tamminen 1962, Hakkila 1966, Velling 1974, Björklund and Walfridsson 1993). Contradictory to the continuous increase in basic density from the north to the south in this study, Hakkila (1979) and Ståhl (1988) reported the highest basic densities in the central parts of Finland and Sweden and a clear decrease towards the north and south, that is, the basic density was found to decrease towards the extreme latitudes of the natural range of the species. In this study, no such trend was observed despite the rather small differences in basic density between the three most southerly regions (Fig. 4). On the other hand, any true continuum of latitudes was not covered in the sampling. Moreover, the effective temperature sum and, thus, the diameter growth pattern are considerably affected by the altitude and slope direction in addition to the latitude.

Few older studies could be found considering the dependency of Scots pine wood density on the different background factors simultaneously at different hierarchical levels. In addition, the vertical density variation was seldom modeled. In the study of Repola (2006), only the tree and within-tree levels, that is, growth rate, relative height position within a tree, and stem dimensions were found to significantly affect the basic density of Scots pine wood. According to a mixed model analysis by Wilhelmsson et al. (2002), 59% of the total variation in the basic density of Scots pine wood could be explained by growth rate, stem dimensions and number of annual rings, as well as the temperature sum. Where the average latewood proportion was included approximately 65% of the variation could be explained. These results were in accordance with the results from this study. As in this study, the stand level random variance was reported to be insignificant (Wilhelmsson et al. 2002, Repola 2006). In addition, the magnitude of the tree level random variance was congruent with the findings of Wilhelmsson et al. (2002).

The ARH1 structure was found to best describe the variance-covariance structure of basic density at different height positions within a tree. ARH1 assumes unequal variances. In addition, the weaker the correlation of sequential measurements, the longer the distance between measurements is, that is, the density correlation between the butt and top logs is weaker than between the butt and middle logs or middle and top logs, respectively. The ARH1 correlation coefficient ρ was significant at the 0.05 level only in Eq. 4; in Eq. 5, the added background variables explained the interdependence of different height positions precisely enough that ρ could be ignored.

Basic density estimates with acceptable accuracy could be calculated for the entire cross-sections using the regression models for density from the pith outwards (Eq. 11). Random within-tree variation - especially knots as well as other defects and abnormalities, were most probably the major source of the unpredictable variation, as only the average density profiles were used in the calculation. Still, rather unbiased estimates of cross-sectional densities were achieved (Fig. 5).

Considering the shrinkage in radial and tangential direction, and the shrinkage variations as well, the results from this study agreed with the earlier observations for Scots pine (e.g., Jalava 1932, 1933, Stöd 2009), and were parallel to the patterns found in other softwoods resembling pine in shrinkage behavior (Harris and Meylan 1965, Yao 1969, McAlister et al. 1992, Watanabe et al. 1998, Usta and Guray 2000, Yamashita et al. 2009a,b). In addition, the variations in shrinkage were observed to follow similar patterns to those in basic density; that is, the variation decreased from the butt upwards, and the smallest variations were found in the north in this study. No significant differences were found at the levels of average shrinkage anisotropy values between the regions; instead, most uniform average pith-to-bark anisotropy patterns were found in the top logs, as well as in the north (Fig. 7).

With respect to basic density and shrinkage of Scots pine wood, more homogeneous raw material for several demanding applications in, for example, joinery, interior, and furniture industry could be procured from the north compared to more southern latitudes. Especially the within-tree (pith-to-bark and butt-to-top) variations decrease from the south to the north. In parallel, the average level of radial and tangential shrinkage is the lowest in the north.

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ВАРИАЦИИ ПО ОБЩЕЙ ПЛОТНОСТИ, УСУШКЕ И АНИЗОТРОПИИ УСУШКИ СОСНЫ ОБЫКНОВЕННОЙ ИЗ ЗРЕЛЫХ ДРЕВОСТОЕВ ФИНЛЯНДИИ И ШВЕЦИИ

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Резюме

На основе эмпирических данных из пяти географических точек Финляндии и Швеции изучались вариации по общей плотности, радиальной и тангенциальной усушке, а также анизотропии усушки зрелой древесины сосны обыкновенной. Возраст камбия лучше показывал вариацию по общей плотности и тангенциальной и радиальной усушке от сердцевины до коры, нежели расстояние от сердцевины. Модель вариаций по радиальной плотности оценивалась на уровне поперечного среза, и она объясняла примерно 50% вариации плотности в срезах. На основании смешанной модели анализа со структурой повторных замеров было объяснено примерно 52% вариации по общей плотности на уровне поперечного среза по географическому происхождению и высотному положению на дереве. Путем добавления переменных, описывающих деревья и древостои более точно, можно объяснить примерно 64% общей вариативности внутри деревьев, между деревьями, древостоями и регионами. В обоих случаях, случайные колебания внутри дерева и между деревьями были статистически значительны. Значительно на вариативность изучаемых характеристик влияло географическое происхождение, в особенности снижалась вариативность на уровне дерева с юга на север. С другой стороны, на севере наблюдался самый низкий уровень радиальной и тангенциальной усушки и общей плотности.

Ключевые слова: *Pinus sylvestris*, сосна обыкновенная, качество древесины, общая плотность, усушка, линейная смешанная модель, повторные замеры