COLOR AND COLOR UNIFORMITY VARIATION OF SCOTS PINE WOOD IN THE AIR-DRY CONDITION

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ABSTRACT

Appearance has an important influence on people's impression and valuation of wood products. One of the major factors that affects the appearance of wooden surfaces made of pine is the simultaneous presence of sapwood and heartwood as these components can vary considerably in color, and large differences between them can affect value and end-uses. In this paper, the color of Scots pine wood in the air-dry condition is discussed in terms of CIE *L*a*b** color parameters and calculated color uniformity parameters between heartwood and sapwood from samples collected from stands in five geographical regions in Finland and Sweden. The background of the differences in color parameters is also discussed. There were significant differences in color parameters between heartwood and sapwood; in addition, geographical origin and sampling height within a tree had significant effects on color of both heartwood and sapwood. Some differences were also found between regions and heights in the color uniformity parameters. However, concerning the practical applications, the results should be considered as indicative due to several departures from conventional practices.

Keywords: CIE *L*a*b**, linear mixed models, *Pinus sylvestris*.

INTRODUCTION

Scots pine (*Pinus sylvestris* L.) wood tends to have large variations in material properties related to silvicultural history and geographical location of the stands where the trees were grown. Additionally, the level and variation in those properties are most probably different compared to other competing tree species and substituting non-wood materials in the main market segments. Aesthetic properties and visual impression affect people's choices when they are selecting, for example, interior materials or furniture. However, measuring people's preferences regarding wood appearance and determining the properties that actually affect the consumers' choices are far from straightforward. In general, two qualitative gross features are said to be important in people's impression and valuation of wood: the overall blend of wood features and the presence or absence of divergent features that mismatch in the surface. In other words, for knotty surfaces, questions of harmony and color balance are important (Broman 2000). Using images of stones and wood, Nakamura et al. (1994) concluded that pattern anisotropy is one of the most important visual factors that influence the psychological images of "wood looking." "Too much" of some wood feature, for instance color variation or number of knots, may cause imbalance in the appearance of a wood surface (Broman 2000). Nakamura et al. (1993) drew similar conclusions when studying preferences for wood wall panels, as they showed that the smaller the knot ratio, the more "agreeable" the wall panel became. In addition to knots, one of the major factors causing imbalance in wooden surfaces made of pine is the simultaneous presence of sapwood and heartwood, due to their quite large natural color difference, which actually tends to increase with time, and possibly different grain patterns.

The red hue of wood is commonly associated

with the extractive content of wood; accordingly, correlations between the redness values and the extractive contents of wood have been reported both for deciduous trees (Yazaki et al. 1994) and conifers (Gierlinger et al. 2004). On the other hand, the yellow tones of wood are primarily governed by the photochemistry of the essential wood components, particularly lignin (Nimz 1973; Yazaki et al. 1994). According to Hon and Glasser (1979), substances causing yellowing were generated by lignin and lignin derivatives, such as quinones, quinone methides, and stilbenes. Furthermore, it has been reported that, especially during irradiation with UV light, cellulose may turn yellow; this yellowing is attributed to the production of oxygen-containing groups, such as carbonyl, carboxyl, and hydroperoxide groups (Kleinert and Marraccini 1966a, 1966b; Hon 1979). On the other hand, there were found no significant correlations between the redness values ($a*$) and the extractive content in Scots pine heartwood (Harju et al. 2006). Instead, the lightness ($L*$) of wood powder correlated negatively, and the yellowness ($b*$) correlated positively with the resinoic and phenolic acid content of Scots pine heartwood.

The aim of this study was to map the levels of, and variations in, color and color uniformity parameters of Scots pine wood from five geographical regions in Finland and Sweden. Linear mixed model analyses were executed to analyze the dependence of these parameters on geographical origin, height within a tree, and other background independent variables while accounting appropriately for the hierarchical structure within the data.

MATERIALS AND METHODS

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). In each region, the stands were selected randomly to represent different forest sites and age classes, as well as to cover the geographical variation of pine stands.
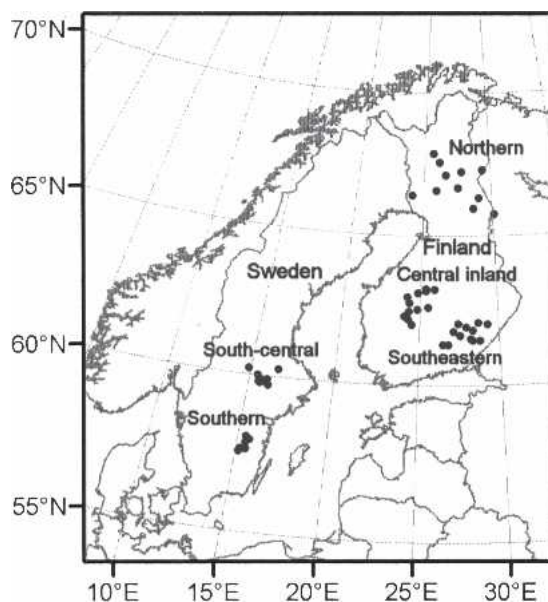

FIG. 1.   Location of the 60 stands sampled in five regions in Finland and Sweden. Map: V. Nivala & A. Lukkarinen, Metla.

In Finland, the sampling was based on the sample plot network of the latest National Forest Inventory (NFI); in Sweden, on the records of the landowner, Sveaskog Ltd. In each stand, three randomly selected Scots pine trees from the diameter range of conventional saw log and small-diameter log trees (DBH ≥ 14-cm) were felled for sampling. A more detailed description of the sample trees is shown in Table 1. From each sample tree, 70-cm bolts were cut from the sections of butt log, middle log, and top log (at 2-, 6-, and 10-m heights, respectively). The bolts were cut into approximately 30-mm-thick full width boards, and the boards were slowly dried at room temperature. In order to be able to determine the possible color changes that resulted from storing of wood, two datasets were produced for the measurements. Dataset 1 consisted of the boards next to the pith-enclosed core board (N = 486). Dataset 2 consisted of a total of 446 smaller specimens produced from dataset 1. Before measurements, the inner face of each board was planed, and the specimens were stored in the dark at constant conditions (+20°C, RH 65%). The specimens of dataset 2 were

TABLE 1. *Basic description of sample trees in different regions.*

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

stored in above-mentioned conditions approximately 2–3 months before measurements, whereas dataset 1 was measured within a few days from planing.

In dataset 1, the color of each board was measured at eight points, four points from both sapwood and heartwood, whereas in dataset 2, a total of four measurements were made on each specimen, two from both sapwood and heartwood. The measurement points were determined and placed evenly on the surface, avoiding knots, knot surroundings, and other defects. Due to the occurrence of defects, however, the number of measurements had to be reduced in some boards and specimens. The points were placed as close as possible to the sapwood-heartwood boundary, i.e., the measurements were executed from the sections of outer heartwood and inner sapwood. Total number of measurements was 3765 in dataset 1 and 1784 in dataset 2. The color was measured either by the spectrophotometric or the tristimulus method. In dataset 2, a spectrophotometer (Minolta CM-2002) with a D_{65} standard illuminant and a 2° standard observer was used, whereas in dataset 1, the color in a part of the boards was measured with the above-mentioned instrument, and in the rest of the boards by the tristimulus method with a chromameter (Minolta CR-300) using a D_{65} standard illuminant. The specular component was included in both measurements. Each measurement was executed exactly in the same direction in the tangential surface of the boards and specimens, and each measurement represented average color in a circular integration area of approximately 113 and 201 mm^2 in spectrophotometer CM-2002 and chromameter CR-300, respectively.

For each point of measurement, the CIELAB (L^*, a^*, and b^*) color parameters (Hunt 1998) were recorded. Here, L^* refers to lightness, a^* to redness, and b^* to yellowness. The averaged values of multiple measurements of L^*, a^*, and b^* were used to represent the entire area of sapwood and heartwood of each board and specimen, respectively. In addition to CIELAB parameters, the reflection spectra in the 400–700nm region at 10nm steps were obtained from the measurements executed with the spectrophotometer.

The color uniformity was calculated as a difference in the lightness (ΔL^*) and chromaticity parameters (Δa^* and Δb^*) between sapwood and heartwood using the following formulae:

$$\begin{aligned} \Delta L^* &= L_s^* - L_h^* \\ \Delta a^* &= a_s^* - a_h^*, \\ \Delta b^* &= b_s^* - b_h^* \end{aligned} \qquad (1)$$

where s refers to sapwood and h to heartwood. In addition, the total color difference between sapwood and heartwood was calculated as

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}}. \qquad (2)$$

For each dataset, general descriptive statistics were calculated. The datasets were compared by means of paired-sample t-tests. The main aim of the study was identifying the variables affecting color and color uniformity; the variations of color parameters (L^*, a^*, b^*) in heartwood and sapwood, as well as the variations of color uniformity parameters (ΔL^*, Δa^*, Δb^*) were analyzed by means of linear mixed models with SPSS for Windows 13.0 software. The F test was used to test the significance of each independent variable (factor or covariate) included into the model; in addition, the significance of

covariance parameters was tested by the *Wald Z* test.

The structure of the basic mixed model used for individual color parameters (*L**, *a**, *b**) was

$$Y = \mu + region + stand + tree + height \\ + heart/sap + \varepsilon, \qquad (3)$$

where *region, height*, and *heart/sap* were treated as fixed factors, and *stand* and *tree* as random variables. When studying the color uniformity parameters (Δ*L**, Δ*a**, Δ*b**), the variable indicating the belonging of sample to heartwood or sapwood (*heart/sap*) was removed from the basic model. In order to describe the variations as precisely as possible, attempts were made to improve the obtained basic models by adding extra factors and/or covariates from a variety of stand- and tree-level background variables (best-fit models). To ensure the fit of both types of models, the residuals were examined as a function of predicted values and also the normal distribution of residuals was checked. The models were fitted using dataset 1, and the same independent variables were used for dataset 2.

<center>RESULTS</center>

Reflectance spectra of sapwood and heartwood

The relative reflectance of both heartwood and sapwood intensified with increasing wavelength in the range of visible light (wavelength 400–700nm). There was a clear difference in the average spectra of heartwood and sapwood. Compared to heartwood, the color of sapwood was unambiguously lighter as the relative reflectance was higher regardless of wavelength (Fig. 2). The standard deviations of reflectance values of both heartwood and sapwood were largest in the middle, and decreased towards both ends of the visible light spectra. The reflectance difference between heartwood and sapwood first increased up to 440–450nm and after that decreased quite linearly with the increasing wavelength. In relation to wavelength, the average difference between heartwood and sapwood ranged from 1.4 to 5.7 percentage points at 400nm and 450nm, respectively.
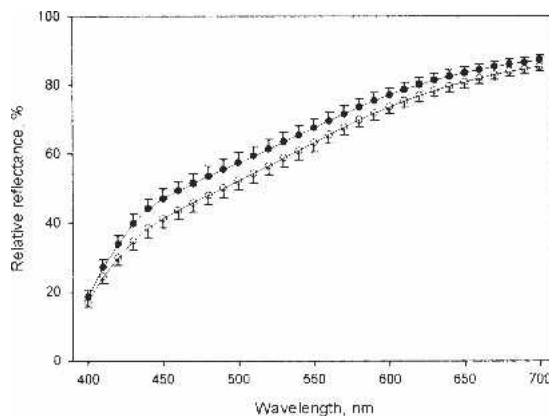

FIG. 2.   Relative reflectance of sapwood (filled symbols) and heartwood (open symbols) in the range of visible light in dataset 2 (average ± standard deviation). For clarity, the standard deviations are drawn only in one direction.

Variation of color parameters

Sapwood was generally lighter in color compared to heartwood (Fig. 2). In addition, the hue of sapwood was paler compared to heartwood as both chromaticity parameters were clearly lower in sapwood than in heartwood. In other words, the saturation of color was higher in heartwood than in sapwood.

The two datasets were not identical, as only the average lightness of sapwood did not differ between datasets, whereas all the other parameters differed significantly at 0.001-level (Table 2). In dataset 1, the average standard deviations of color parameters within sample boards (calculations based on four measurements from each) were 0.39 for lightness (*L**), 0.20 for redness (*a**), and 0.31 for yellowness (*b**) in sapwood. In heartwood, the respective values were 0.49 for *L**, 0.26 for *a**, and 0.38 for *b**.

The coefficient of determination of the basic model (Eq. 3) for lightness (*L**) was 0.50 in dataset 1 and 0.58 in dataset 2. All variables of the basic models were statistically significant in both datasets (Table 3). Compared to basic models, the explanatory power of best-fit models was only slightly better, 0.53 and 0.62 in datasets 1 and 2, respectively. In the best-fit models, tree age and tree height were included as covariates in addition to the basic model pa-

TABLE 2. *Color parameters of heartwood and sapwood in datasets 1 and 2 (average ± standard deviation). Bold values indicate significant differences at 0.001 level between datasets 1 and 2.*

Dataset	Heartwood			Sapwood		
	L^*	a^*	b^*	L^*	a^*	b^*
1	**84.47** ± 1.23	**3.97** ± 0.77	**22.68** ± 1.01	86.23 ± 1.21	**3.50** ± 0.69	**20.17** ± 0.93
2	**84.10** ± 1.26	**3.49** ± 0.75	**23.18** ± 1.23	86.24 ± 1.22	**2.71** ± 0.61	**20.70** ± 1.09

TABLE 3. *Tests of fixed effects in the basic models for* L^*, a^*, *and* b^* *in datasets 1 and 2. Dfn = numerator degrees of freedom, dfd = denominator degrees of freedom, F = test value. Bold values indicate significance at 0.05 level.*

		L^*			a^*			b^*		
		dfn	dfd	F	dfn	dfd	F	dfn	dfd	F
Dataset 1	Intercept	1	51	**1590975**	1	48	**9851**	1	49	**67574**
	Region	4	50	**16.08**	4	48	**31.44**	4	49	2.393
	Height	2	751	**83.57**	2	751	**40.68**	2	736	**151.3**
	Heart/Sap	1	735	**839.1**	1	734	**168.4**	1	724	**3625**
Dataset 2	Intercept	1	49	**1466201**	1	47	**7389**	1	48	**61231**
	Region	4	49	**14.51**	4	47	**4.625**	4	48	2.086
	Height	2	733	**63.15**	2	738	**28.87**	2	715	**43.21**
	Heart/Sap	1	715	**1298**	1	718	**396.5**	1	699	**2076**

rameters. Most of the variation of chromaticity parameters (a^*, b^*) could also be described by the basic models, and the best-fit models gave only slightly better coefficients of determination: for redness the coefficients of determination of the basic models were 0.36 and 0.33 and for yellowness 0.69 and 0.61 in datasets 1 and 2, whereas the coefficients of best-fit models were 0.38 and 0.35 for redness and 0.74 and 0.66 for yellowness, respectively. For redness, all basic model variables were significant at 0.001 level in dataset 1, whereas the significance of region was 0.003 and other variables less than 0.001 in dataset 2 (Table 3). The best-fit model was achieved by adding mean elevation above sea level and height to live crown to the model. The latter was significant at 0.001 level in both datasets, whereas elevation was significant at 0.05 level only in dataset 1. In both datasets the effect of region was not statistically significant in basic model of yellowness, whereas other variables were significant at 0.001 level (Table 3). For the best-fit model, tree age was added, being significant at 0.001 level in a similar manner to all the other variables.

Based on analyses of the basic and best-fit models in datasets 1 and 2, wood lightness dif-

fered significantly between heartwood and sapwood and intensified significantly with increasing height position in the tree. Lightness was significantly higher in the north than in other regions and the difference was clear especially in sapwood (Fig. 3a). Based on pair-wise comparisons, the two regions in southern Sweden and the two in central-southern Finland did not differ significantly from each other, whereas some differences could be found between other regions depending on the model and dataset used.

Both chromaticity parameters were higher in heartwood than in sapwood. In general, redness and yellowness of both heartwood and sapwood decreased with increasing height position in the tree, regardless of region. In both datasets, the redness of sapwood increased as latitude decreased, while in heartwood an opposite relationship was found in dataset 2 (Fig. 3b). Concluded from the pair-wise comparisons, the northernmost region was found to differ from all other regions in dataset 1, whereas the only differences were found between northern Finland and both southeastern Finland and southern Sweden in dataset 2. In addition, these differences became insignificant in the best-fit models
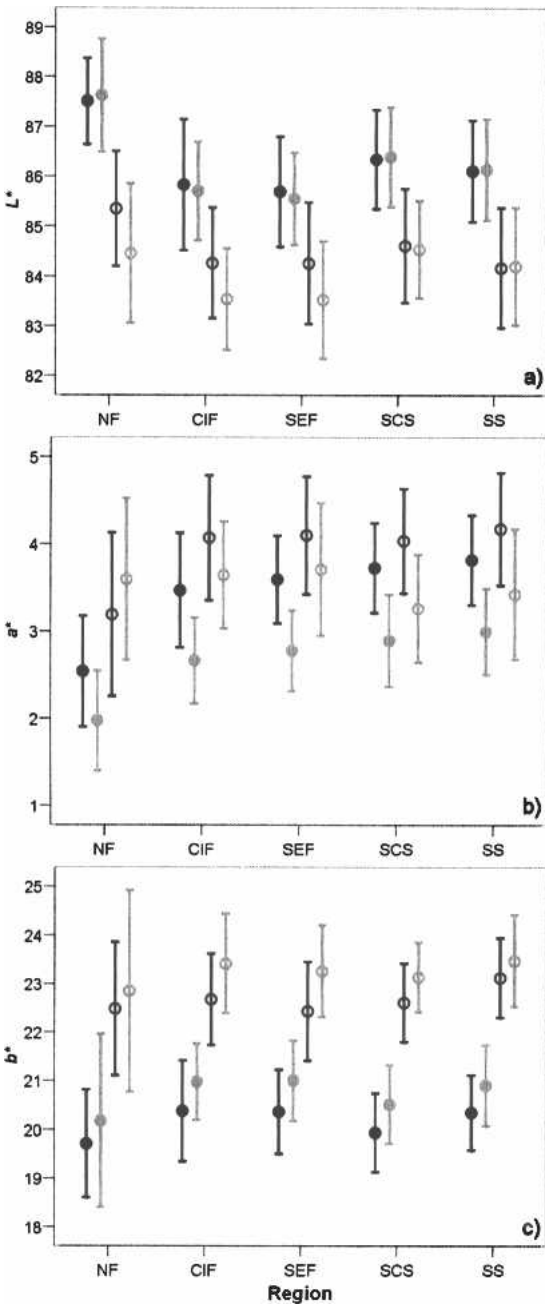
FIG. 3a–c. Averages and standard deviations of color parameters L^*, a^*, and b^* in the five regions in datasets 1 (black) and 2 (grey). Filled symbols = sapwood, open symbols = heartwood.

as more dependent variables were added. As mentioned earlier, there were no significant differences between regions in the structure of the basic models for yellowness, but after adding tree age to the independent variables list (best-fit models), the effect of region became significant, and northern Finland differed significantly from all other regions in both datasets (Fig. 3c).

If the models were constructed separately for heartwood and sapwood, moderate changes in the coefficients of determination could be found in both the basic and best-fit models. For lightness, the explanatory power of the separate models was lower in both datasets compared to combined models where heartwood and sapwood were both included. The most dramatic decrease could be found in the models describing the variation of yellowness, which indicates that most of the variation in yellowness can be explained by knowing only whether the wood is of heartwood or sapwood. In the analysis of redness values, the coefficients of determination of sapwood models were higher compared to the combined models, whereas in heartwood models, the situation was reversed and remarkably low R^2 values were achieved, especially in dataset 2.

The total random variance of lightness was almost equal in both datasets, while in redness and yellowness the total variance was moderately larger in dataset 2 than in dataset 1. Concerning lightness, the between-tree variation was the source of 21%, between-stand variation approximately 12%, and residual variation approximately 67% of the total random variation. For redness, the sources were quite similar to lightness, whereas in yellowness the proportion of residual variation was clearly smaller and between-stand variation much larger compared to the variance structure of other color parameters (Table 4).

Variation of color uniformity

The average values of color uniformity parameters ΔL^*, Δa^*, and ΔE^* differed at 0.001 level between datasets 1 and 2, and the highest absolute values were found in dataset 2. On the other hand, the average difference in yellowness

TABLE 4. *Estimates of covariance parameters in the basic models for* L*, a*, *and* b* *in datasets 1 and 2. The proportional values are shown in parentheses. Bold values indicate significance at 0.05 level.*

Covariance parameters	L*		a*		b*	
	Dataset 1	Dataset 2	Dataset 1	Dataset 2	Dataset 1	Dataset 2
Stand	**.122 (11)**	**.143 (13)**	.026 (7)	.025 (6)	**.278 (32)**	**.312 (26)**
Tree	**.243 (21)**	**.239 (21)**	**0.95 (25)**	**.072 (17)**	**.226 (26)**	**.247 (20)**
Residual	**.780 (68)**	**.756 (66)**	**.265 (69)**	**.329 (77)**	**.375 (43)**	**.655 (54)**
Total	1.145 (100)	1.138 (100)	.386 (100)	.426 (100)	.879 (100)	1.214 (100)

between sapwood and heartwood (Δb^*) was statistically equal in both datasets (Table 5).

In dataset 1, there were no significant differences in ΔL^* between regions (Fig. 4a) and between sampling heights, whereas in dataset 2 both factors were significant at 0.001 level: the values were clearly biggest in the northernmost region, while the differences between the other regions were not significant. In addition, ΔL^* tend to increase with increasing sampling height, and values at the height of 2m differed significantly from the ones at 6m and 10m. In dataset 1, the average values of ΔL^* ranged from 1.40 to 2.09 in southeastern and northern Finland, and, in dataset 2, from 1.88 to 3.10 in south-central Sweden and northern Finland, respectively.

The absolute values of Δa^* decreased from the north to the south in dataset 2, whereas in dataset 1 the values were more equal between regions and no significant differences were found (Fig. 4b). In dataset 1, the average values ranged from −0.33 to −0.65 in south-central Sweden and northern Finland, whereas in dataset 2 the values ranged between −0.40 in southern Sweden and −1.59 in northern Finland, respectively. Based on the pair-wise comparisons, three regions could be distinguished in dataset 2: northern Finland, southern and central Finland, and southern and central Sweden. In both datasets, the effect of height on Δa^* was

TABLE 5. *Differences in color parameters between sapwood and heartwood (Eq. 1 & 2) in datsets 1 and 2 (average ± standard deviation). Bold values indicate significant difference at 0.001 level between datasets 1 and 2.*

Dataset	ΔL^*	Δa^*	Δb^*	ΔE^*
1	**1.75** ± 1.21	**−0.46** ± .71	−2.49 ± .86	**3.30** ± 1.13
2	**2.12** ± 1.22	**−0.76** ± .84	−2.51 ± .90	**3.55** ± 1.34

significant: absolute values increased with increasing sampling height. Nevertheless, the difference was significant only between 2m and 10m in dataset 1, and between 2m and both 6m and 10m in dataset 2, respectively.

Considering Δb^*, no such clear trends between regions were found in the datasets, and the only significant differences were found between southeastern Finland and both regions in Sweden in dataset 1 (Fig. 4c). Again, the absolute values of Δb^* increased with increasing height in both datasets. In dataset 1, only 10m differed from both 2m and 6m, whereas in dataset 2, the significant differences were found between 2m and the two other heights. In dataset 1, the average values of Δb^* ranged from −2.01 in southeastern to −2.62 in northern Finland. The respective values of dataset 2 were −2.20 in southeastern and −2.70 in northern Finland. The interpretation of ΔE^* was more difficult compared to other color uniformity parameters, and thus only the average values of ΔE^* are presented. In dataset 1, the average ΔE^* values ranged from 3.18 to 3.53 in central inland and northern Finland, whereas in dataset 2 the values ranged from 3.22 to 4.50 in southeastern and northern Finland, respectively (Fig. 4d).

The coefficients of determination of above-described basic models for ΔL^*, Δa^*, and Δb^* were notably low in both datasets, ranging from 0.04 to 0.26. The best-fit models were not appreciably better compared to the basic models, i.e., adding more independent variables did not improve the basic models in a similar manner as it did when considering the individual color parameters of sapwood and heartwood. Again, the residual variance was the main source of the total random variance, whereas tree-level vari-
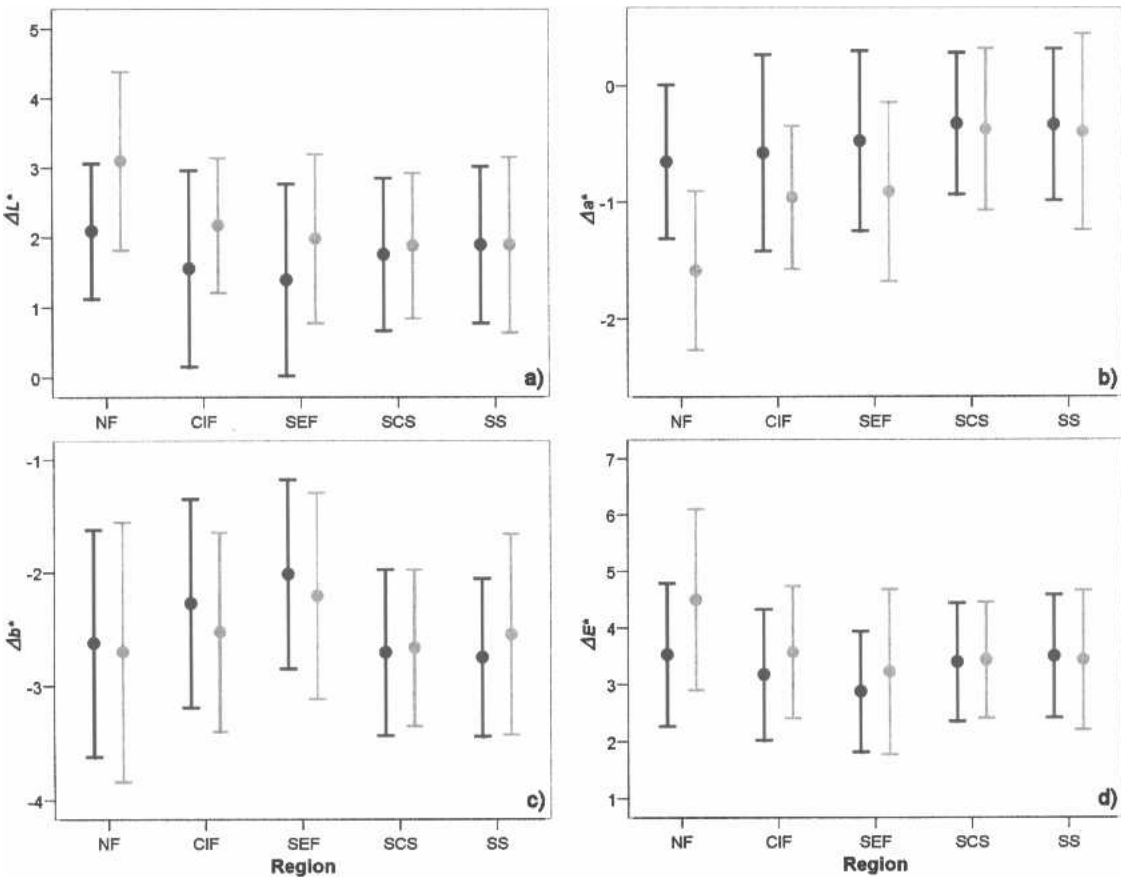
FIG. 4a-d.   Averages and standard deviations of color uniformity parameters ΔL^*, Δa^*, Δb^*, and ΔE^* in the five regions in datasets 1 (black) and 2 (grey).

ance accounted for approx. 20 to 40% and stand-level variance approx. 10% of the total variance (Table 6).

DISCUSSION AND CONCLUSIONS

The two datasets differed significantly from each other, indicating that some changes took place during the after-planing storage period of the specimens of dataset 2. The boards were stored in piles in a dark room at constant temperature and RH; therefore, the subsequently discovered changes in color were probably caused by alterations in the concentrations of chemical compounds. The most dramatic changes were found in the chromaticity param-

TABLE 6.   *Estimates of covariance parameters in the basic models for* ΔL^*, Δa^*, *and* Δb^* *in datasets 1 and 2. The proportional values are shown in parentheses. Bold values indicate significance at 0.05 level.*

	ΔL^*		Δa^*		Δb^*	
Covariance parameters	Dataset 1	Dataset 2	Dataset 1	Dataset 2	Dataset 1	Dataset 2
Stand	.152 (10)	.156 (12)	.049 (10)	.040 (7)	**.111 (16)**	.097 (12)
Tree	**.342 (23)**	**.306 (23)**	**.202 (40)**	**.213 (40)**	**.247 (35)**	**.172 (22)**
Residual	**.975 (66)**	**.866 (65)**	**.254 (50)**	**.280 (53)**	**.339 (49)**	**.522 (66)**
Total	1.469 (100)	1.328 (100)	.505 (100)	.533 (100)	.697 (100)	.791 (100)

eters: redness clearly decreased and yellowness simultaneously increased during storage. On the other hand, the lightness of sapwood did not change, but heartwood darkened during the storage. In general, spectrophotometric instruments provide higher accuracy compared to tristimulus instruments (Hunt 1998); however, no differences were found in this study between the measurement data gained using either detection method (spectrophotometer or chromameter).

Green pine wood contains substantial amounts of volatile organic compounds (VOC), predominantly aldehydes, acetone, and considerable concentrations of terpenes (mainly α-pinene), Δ^3-carene, and limonene, and the concentrations decrease over time as the compounds vaporize (Jensen et al. 2001). α-pinene, Δ^3-carene, and β-pinene together account for 86–98% of the total VOC content in Scots pine (Englund and Nussbaum 2000). During the drying and storing of wood, a high proportion of monoterpenes is lost through evaporation (Englund and Nussbaum 2000), whereas a large proportion of the resin acids stay in wood. Monoterpenes are evaporated from both heartwood and sapwood, and, after kiln-drying, the amount of monoterpenes is still clearly larger in heartwood than in sapwood (Englund and Nussbaum 2000). As the wood specimens used in this study were slowly dried at low temperature conditions, it could be concluded that the extractive concentration had not declined significantly during the drying phase, and some vaporizing was still occurring during the storage period of dataset 2 partly causing the decrease in the redness of wood. In addition to vaporizing, both autoxidative and enzymatic processes take place during wood storage. Oxygen attacks double bonds in extractives and initiates a chain reaction that generates free radicals, which include particularly strong oxidants (Sjöström 1992).

The chemical pathways of yellowing during time are not fully understood (Ek 1992), but the oxidation of the phenoxy radical to the yellow *o*-quinone has long been recognized as a key factor involved (Hu et al. 1999). It is known that oxygen, albeit in small amounts, has to be present (Leary 1968; Andtbacka et al. 1989), and

the yellowing is accelerated by the action of heat and/or UV light (Nolan 1945). As the specimens were stored in a dark environment, the yellowing occurred as a result of the presence of oxygen only. It can be assumed that the same phenomena affecting yellowness of wood during storage are also connected with the decrease in lightness of heartwood in dataset 2.

The differences in color parameters between heartwood and sapwood can be mainly explained by their different chemical composition. The greater lightness of wood from northern Finland is probably due to lower earlywood percentage and lower density in this region compared to the other regions. As the lignin proportion is higher in earlywood than in latewood (Fengel 1969; Fukazawa and Imagawa 1981; Fengel & Wegener 1984), and the earlywood proportion increases from the north to the south, it can be assumed that the lignin proportion is larger in the south compared to wood with a more northerly origin. This is supported by the findings of Hildebrandt (1960), who concluded that warm climate favors lignin production and wood from warm conditions is therefore rich in lignin, and Hinterstoisser et al. (2001), who concluded for Scots pine trees from northern Finland that the average lignin content is larger the more southerly the point of origin. Based on these findings, it could be concluded that at least a part of the increase in the yellowness of wood from the north to the south is caused by the increase in lignin content. On the other hand, the positive correlations between the yellowness values and the content of certain extractives may also affect the differences in yellowness between the regions (Harju et al. 2006).

In general, as the earlywood proportion is smallest at the stump height, and rises with increasing height (Kärkkäinen 2003), also the amount of lignin can be assumed to follow the same pattern. A slight increase in the average proportion of lignin with increasing height has been reported for small Scots pine trees (Nurmi 1991; Voipio & Laakso 1992), and also for bigger trees of Scots pine and other pines (Larson 1966; Upprichard 1971; Upprichard and Lloyd 1980). As a conclusion, the measured decrease

in yellowness from the 2-m to the 10-m section cannot be explained by the variations in the lignin proportion.

In heartwood of Scots pine, the average proportion of extractives slightly increases with the increasing latitude, whereas the average total extractive proportion in sapwood does not change from the south to the north (Hakkila 1968). According to unpublished results by Grekin (2006), the total amount of phenolic compounds does not differ between these five regions in sapwood nor in heartwood. On the other hand, the VOC proportion in heartwood is slightly larger in the north than in the south before and after kiln-drying, whereas in sapwood the largest proportions are found in the south (Englund and Nussbaum 2000). In addition, other factors such as tree age also to some extent affect the proportion of extractives (Hakkila et al. 1995). As the red hue was higher in both heartwood and sapwood the more southerly the point of origin, the differences in redness were caused by other factors than extractives. This is supported by the findings of Harju et al. (2006), who found no significant correlations between the redness values and the extractive content in Scots pine heartwood. Yet again, the differences in ring width and earlywood proportion may have a background effect making it difficult to separate out the causal factors. The extractive proportion of sapwood does not vary with height in the stem (Kärkkäinen 1981), whereas in heartwood the largest proportions of extractives are found close to the base (Kärkkäinen 1981; Tyrväinen 1995). On the other hand, as the number of knots is the largest in the top of the tree, the total extractive proportion is again increasing above the base of live crown (Hakkila et al. 1995). Based on these findings, the discovered decrease in red hue with increasing height might be caused by the decrease in the amount of the extractives, but the effect of ring width and earlywood proportion should also be considered.

The differences in color uniformity parameters in datasets 1 and 2 were due to differences in individual color parameters between datasets. The difference in lightness parameters was larger in dataset 2 than in dataset 1, whereas the values of $\Delta a*$ and $\Delta b*$ were higher in dataset 1 than in dataset 2, with an exception of $\Delta b*$ in south-central and southern Sweden. Also the total differences $\Delta E*$ were largest in dataset 2 in all regions, except southern Sweden. As a conclusion, the heterogeneity of redness and yellowness of wood decreased during the storage, whereas a slight increase in the heterogeneity of lightness could be found. The increase in $\Delta E*$ during the storage was larger the more northerly the point of origin.

The average absolute values of $\Delta L*$ and $\Delta a*$ were highest in the northernmost region. Wood from northern Finland was slightly more heterogeneous in $\Delta L*$ compared to other regions, and no such large variation in $\Delta L*$ was found between other regions. Accordingly, $\Delta a*$ increased with the increasing latitude. No clear latitudinal trend was found in $\Delta b*$, since the average values of $\Delta b*$ did not differ between northern Finland and south-central and southern Sweden, and the values in central inland and southeastern Finland were somewhat higher compared to the three other regions.

Models describing $L*$ and $b*$ had fairly high R^2 values, whereas the fits of the $a*$ models were clearly lower. Adding variables to the models only slightly improved the degrees of determination, indicating that most of the variation that can be explained by the background factors is described by region and sampling height. As an exception, the yellowness of wood was statistically independent of region, and the *heart/sap* variable was the main factor affecting it, the same way as it affected also the other color parameters. The dependence of uniformity parameters $\Delta L*$, $\Delta a*$, and $\Delta b*$ on the background variables was much weaker or almost insignificant compared to one of individual color parameters.

Relatively large variations were found in covariance parameters of the mixed models between the datasets. For both individual color parameters $L*$, $a*$, and $b*$ and color uniformity parameters $\Delta L*$, $\Delta a*$, and $\Delta b*$, most of the total random variation was caused by the within-tree variation (residuals), ranging from 43 to 77%. The within-tree variation was larger in heart-

wood than in sapwood. Within a stand, tree-to-tree variation was at a significant level, accounting for 17 to 40% of the total random variation. Instead, the between-stand variation within a region was relatively low, approximately 5–15%; the proportion exceeded 25% of the total random variation only for yellowness.

Concerning the practical applications, the results obtained in this study should be considered as indicative for several reasons. In commercial kiln-drying, large amounts of extractives are evaporated, resulting in lower extractive proportions in dried lumber. On the other hand, the relatively high temperatures used in kiln-drying accelerate the chemical reactions, cause remarkable changes in the chemical composition, and thus affect the color of wood. Besides, UV radiation affects wood color quite rapidly if the wood is not appropriately finished. Nevertheless, it seems that in the air-dry condition, the wood from the north is lighter and paler compared to more southern origins, but the color difference between heartwood and sapwood is more uniform in the south than in the north. Since a significant part of the variation in color parameters is found within single trees and between trees within single stand, the possibilities of controlling the variation by the appropriate allocation of raw materials into different end-uses is complicated.

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