MODELLING WATER SORPTION GRADIENTS IN SPRUCE WOOD USING CT SCANNED DATA*

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ABSTRACT

Liquid water sorption in the longitudinal direction in wood samples of *Picea abies* (L.) Karst. (Norway spruce) was measured with computed tomography (CT) scanning and image processing and then evaluated using multivariate discriminate analysis. The purpose was to determine if there were any differences in liquid water sorption that could be dependent on the vertical position within the tree (0.8, 5.8, and 9.5 m from the butt cut), the growing site (dry or wet), and the type of tree (suppressed or dominant). Test pieces were CT scanned after 1, 3, 7, and 14 days of water sorption in end grain and during desorption at room temperature. The objective was to find wood suited to exterior use that is durable because it takes up water poorly. The conclusion was that heartwood of spruce absorbs less water than sapwood. Heartwood gradients were generally steeper, with a markedly lower moisture content than sapwood. The moisture content gradient profiles differed between the wet and dry sites during sorption and desorption in heartwood and sapwood. Whether or not the trees had been suppressed or dominant had no impact on the moisture content gradients. There was an indication that moisture content gradients in heartwood differed between the first and the second logs, but in sapwood there was no difference.

Keywords: liquid water sorption; heartwood; computed tomography scanning; image processing; multivariate analysis; *Picea abies*.

INTRODUCTION

The performance of wood and its service life for products in exterior use will be greatly affected by construction practice and the degree of protection from prolonged wetting. For this reason, timber that takes up water poorly and dries quickly has the right properties to resist decay, since a fungal attack in wood starts

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with the presence of moisture. Little water sorption leads to small differences in moisture movement and thereby fewer cracks. High moisture content occurs locally at and around cracks (Ekstedt 2002, in prep.). In these areas there is an increased risk of internal tension and stress resulting in crack initiation and propagation.

Long before forestry had become industrialised, wood for buildings was selected on the basis of differences in quality and function between trees. To know if the wood was suitable, parameters such as crown size, bark features, stem properties, branches, site, colour, etc., were considered in judging quality (Anon. 1985; Sjömar 1988).

The transport of water in wood can be divided into the two main categories of hygroscopic and capillary water transport. Hygroscopic transport is by intergas diffusion and bound water diffusion. Capillary transport involves the passage of fluids through the interconnected voids (lumina) of the wood structure under the influence of static or capillary pressure gradients (Siau 1984). With CT scanning, water distribution during capillary flow can be shown visually and is measurable by image processing. Such scanning has been used in many applications during the last 25 years. Lindgren started in the middle of the 1980s by showing how X-ray attenuation coefficients and CT number can be calculated and related to wood density, wood moisture content measurements, and geometrical reconstruction (Lindgren 1985). Transformed images were then subtracted from the dry reference images to determine moisture content with an algorithm established by Lindgren (1992). The accuracy of the whole process of sampling two images, applying the algorithm, and subtracting the images is size-dependent. As an example, in practice an accuracy of ±1.4% (–level of 0.05) below fibre saturation point and ±4% (–level of 0.05) above fibre saturation point in a 7*7 pixel area (approximately 3*3 mm) can be expected according to Lindgren (1991). It has been used for detection of properties of sawn logs such as knot parameters, strength properties, compression wood, and spiral grain (Grundberg & Grönlund 1997; Oja 1997; Nyström & Öhman 2002; Sepúlveda *et al.* 2002) and during artificial drying of wood (Wiberg 1995; Rosenkilde & Arfvidsson 1997).

The objective of this work was to study the influence of various parameters on water sorption and desorption in Norway spruce. In this study, trees were selected to cover a large difference between parameters that can be expected to govern water distribution in the tree, such as the size of the crown, density, age, and access to water. The object was to investigate whether moisture content gradients after sorption and desorption were different depending on site, height in the trees, or type (suppressed or dominant). Since most damage in outdoor products such as window frames occurs in the end grain because free water from rain absorbs (capillary flow) fastest in the longitudinal direction, liquid water sorption in end grain was studied.

MATERIALS AND METHODS

Materials

Twenty Norway spruce, equal numbers from suppressed (U) and dominant (H) categories, were selected from two sites. One site had a good supply of water, the other site had no free ground water. The spruce from the dry site (T) were grown on a typical "sandy heath", 175 m above sea level, and had an average age of 148 years. The dominant trees in this group had an average diameter at breast height (dbh) of 29 cm, while the suppressed trees had an average 18 cm dbh. The spruce grown on "moist forest land" (F), 250 m above sea level, had an average age of 67 years. The dominant trees in this group had an average 31 cm dbh and the suppressed trees had an average diameter of 19 cm. The trees were felled and cut into 5-m logs which were sawn in the north-south direction to 32-mm-thick boards and dried to 12% mc (Fig. 1). For absorption testing, 200-mm-long specimens were cut from three different heights named Level 1, Level 3, and Level 4 (Fig. 2). Level 2 specimens were taken for another examination.

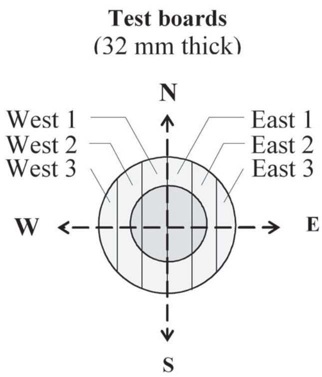

FIG. 1–Sawing pattern

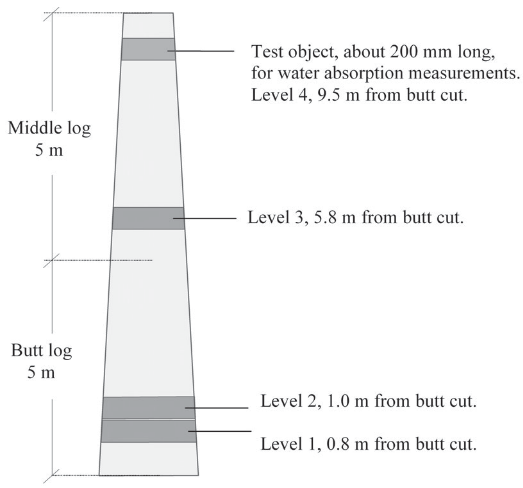

FIG. 2–How the trees were divided and where the test object was located in a stem

Before CT scanning, the test specimens were placed in a climate of standard conditioning at 65% relative humidity and temperature 22ºC (corresponding approximately to an equilibrium moisture content of 12%) for more than 2 months. For Level 1, the sawn flitches from the same tree were assembled with a distance of 12 mm between them into one test object (*see* Fig. 3). To ensure correct repositioning in the CT scanner, lasers were used to mark vertical reference points 100 mm from the end grain. A drill bit (3 mm) was used to make the holes. The flitches for Levels 3 and 4 were separate test objects. Level 1 was not CT-scanned at the same time as Levels 3 and 4. For the test, flitches West 1 or West 2 were used.

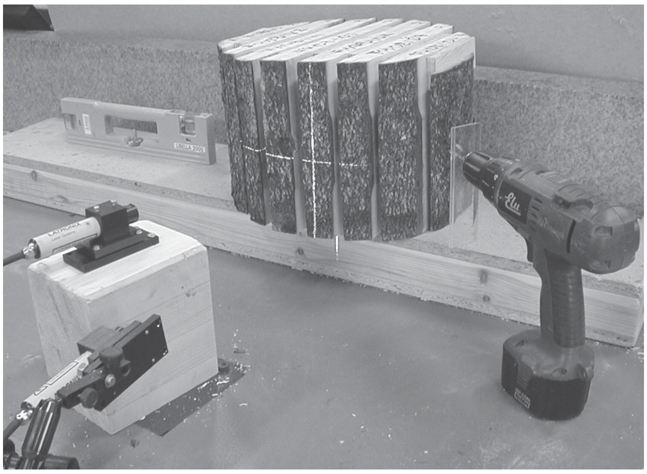

FIG. 3–Sawn flitches

Test objects were placed in a basin on bars of stainless steel in 5-mm-deep tap water for end grain sorption. The measurements were carried out at room climate with the aid of a CT scanner after the specimens had stood for 1, 3, 7, and 14 days with butt ends in water during sorption. The examination followed the grain in the middle of each board, and the scan was 10 mm wide. Desorption was measured at room climate 23° to 25°C over a period of 7 days. The test objects were oven-dried at 103°C and then CT-scanned to obtain the dry reference images that were used in the image processing.

CT Scanning

A CT scanner consists of an X-ray tube and a detector array that rotate around the object being examined. The image is reconstructed with the help of mathematical algorithms, and the image created describes the density variations in the cross-section. The calculated X-ray linear absorption is normalised to the corresponding linear absorption coefficient for water, μ_{water}. This normalised value is referred to as the CT number (Eq. (1)) (Herman 1980), where μ_x was the absorption coefficient for the tested material.

$$CT_{number} = 1000 \times \frac{[\mu_x - \mu_{water}]}{\mu_{water}} \qquad (1)$$

By giving each CT number a certain greyscale value, an image can be evaluated showing the density variation within a slice of the object. A CT scanner, Siemens SOMATOM AR.T, located at Luleå University of Technology was used for the measurements. The CT images were obtained using scan settings of 110 kV, 50 mA, and a scan width of 10 mm. For image reconstruction, a standard Shepp-Logan algorithm was used. All images were stored as 512 × 512 pixels.

Image Processing of CT Images

After CT scanning, raw data images were imported into a software program called Scion Image (Scion Corporation 2005) for image processing. Moisture content measurement using a CT scanner is an indirect measurement method, as the CT number is coupled to the density of wood and water. Two density measurements must be made in order to evaluate moisture content, one with unknown moisture content and one with a known moisture content level as a reference measurement. In this case, the reference level was obtained after the specimens had been oven-dried at 103°C until they were completely dried. Wood swells and shrinks during sorption and desorption, and therefore the images must be geometrically transformed in order for them to be compared. An image-processing algorithm that geometrically transforms images in such a way that the immersed cross-section will be identical to the dry reference cross-section was used. Transformed images were then subtracted from the dry reference images to determine moisture content with an algorithm established by Lindgren (1992). The accuracy of the whole process of sampling two images, applying the algorithm, and subtracting the images is size dependent. As an example, in practice an accuracy of ± 1.4% (α-level of 0.05) below fibre saturation point (FSP) and ± 4% (α-level of 0.05) above FSP in a 7 × 7 pixel area (approximately 3 × 3 mm) can be expected according to Lindgren *et al.* (1991a, 1992) and Lindgren (1991a, b).

The measurements were performed in the sapwood and heartwood, mainly on the south side of the stem, to the left in the images (*see* Fig. 4). When anomalies such

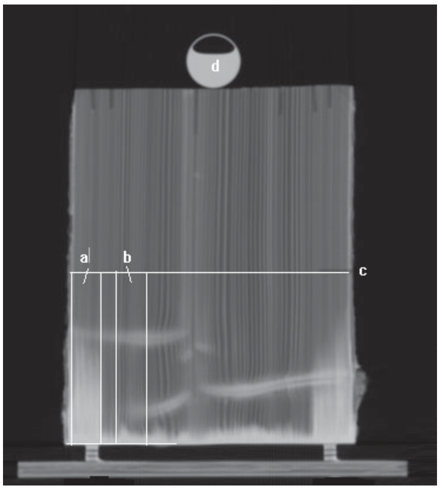

FIG. 4–A vertical cross-section CT image showing absorption after 14 days in water. Points a and b indicate where the gradients were measured in sapwood and heartwood. The gradients in heartwood were measured 12 mm from the sapwood border. Point c is a reference line 100 mm from the bottom surface, and d is a reference jar containing water.

as knots were present, the measurements were done on the north side of the image. Images from flitches west 1 or east 1 (Fig. 1) were used, depending on which one was closer to the pith. The CT image in Fig. 4 shows absorption after 14 days in water.

The intensity in the image is proportional to the amount of water, since there is a linear relationship between density and moisture content. White areas indicate high density, and because of this, increased water content or high moisture content. To ensure that the measurements were done at the same position, reference marks were used. The moisture content gradients were a mean value throughout the width of sapwood and the scan thickness (10 mm). The first two pixels (approx. 1.4 mm) close to the bottom edge were removed in order to eliminate artifacts. To reduce the effect of annual rings, a smoothing function was applied to the gradients based on the average of 11 pixels. The measurements of moisture content level at the surface (MC_{surf}) were an average moisture content of the first five pixels. The capillary water height (CWH) was chosen as the distance from the surface to the point where moisture content reached 20% ($CWH_{20\%}$).

Multivariate Analysis

The moisture content gradients were analysed using a multivariate method with software from Umetrics, SIMCA P+10 (Umetrics AB 2005). The moisture content gradient was expressed as 95 variables (the number of millimetres measured), centred but not scaled. These 95 measurements were used as X-variables in the multivariate analysis. The gradients were “filtered” of abnormal values resulting from knots and other anomalies in the measured area. These anomalies were left as missing values. Principal component analysis (PCA) produces a summary showing how the observations are related and whether there are any deviating observations or groups of observations in the data. Principal component analysis helps to explain which variables contribute with similar information to the principal component analysis model and which variables provide unique information about the observations. Principal component analysis describes the correlation structure in a block of X-variables (X) (Eriksson *et al*. 2001; Martens & Naes 1996). The first principal component explains most of the variation in X, while the second principal component is orthogonal to the first principal component and explains most of the remaining variation. Simca uses cross-validation to define the number of significant principal components. The projection approach can be adapted to a range of data-analytical objectives, i.e., summarising and visualising a dataset, multivariate classification and discriminate analysis, and finding quantitative relationships among variables. The advantages of projection are that it applies to any shape of multivariate data, with many or few variables. It can handle missing, noisy, and highly colinear data.

Partial to least square structure (PLS) is a regression extension of principal component analysis that is used to connect the information in two blocks of variables, X and Y, to each other. PLS-discriminant analysis makes it possible to accomplish a rotation of the projection to give a latent variable that focuses on class separation ("discrimination"). The objective of PLS-discriminant analysis is to find a model that separates classes of observations on the basis of their X-variables (Eriksson *et al*. 2001; Martens & Naes 1996). To evaluate the model, R^2X (explained variance of X-data), R^2Y (explained variance of Y-data), and Q^2 (predicted variance) were used. Predicted variance is based on cross-validation (Eriksson *et al*. 2001). Small differences between explained variance and predicted variance indicate stable models that are not modelling noise. When analysing DmodX (distance to model) and score plot, a 95% confidence interval was used. To validate the models, observations were excluded from the work set while calibration was performed and later used as a test set. In the classification matrix, the predicted value for each response represents the probability of observations belonging to that class. Each observation is classified as belonging to the class for which the probability is the highest.

RESULTS

Variation of Moisture Content Gradients after Sorption in End Grain

Examples of three moisture content gradients show the sorption front as it moves longitudinally into the wood after specimens have soaked in water for 14 days in end grain (Fig. 5). These samples were taken 9.5 m from the butt cut, Level 1. Moisture content at surface (MC_{surf}) was about 170% for the three observations. Moisture content gradient from heartwood (A) was steeper than the gradients from

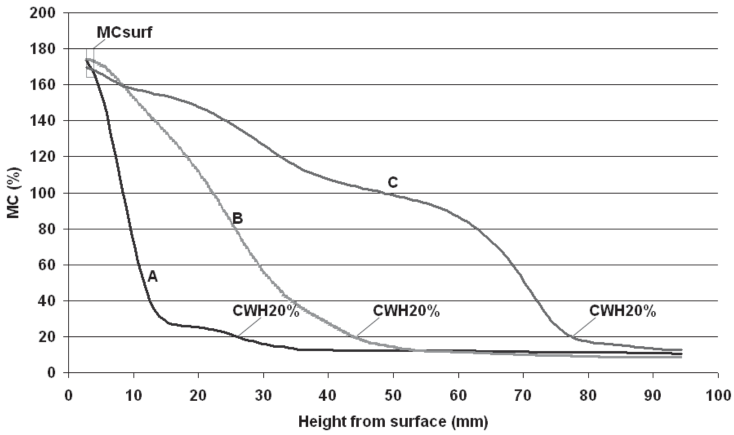

FIG. 5– Examples of three moisture content gradients (A, B, and C) after sorption of liquid water in end grain for 14 days in Norway spruce.

sapwood (B and C). In heartwood, the capillary water height ($CWH_{20\%}$) was about 25 mm as compared to 45 and 78 mm for the sapwood moisture content gradients. As can be seen, sample C had a high moisture content front deep in the wood and a $CWH_{20\%}$ about 3 times higher than sample A. It is desirable to find wood with qualities similar to sample "A", as it is likely to have better durability than C since it becomes less wet, and fungal attacks in wood start with the presence of moisture. In order to separate the moisture content gradients that derive from differences in shape according to growing conditions, multivariate statistical evaluation by PLS-discrimant-analysis was used. A multivariate approach was used in order to be able to use all moisture content values along the measured height (95 variables) and thus follow the change in shape of the moisture content gradients.

Growing site

PLS-discriminant analysis was used to separate moisture content gradients that were dependent on whether trees grew on wet or dry sites. Two classes were used—F for moist forestland and T for dry sandy heath. U indicates suppressed and H dominant trees.

Sorption in heartwood

The score plot is a summary of the relationships among observations. Similar observations are close to each other in the score plot. The multivariate PLS-discriminant analysis shows that site F observations were more frequently grouped to the right and T observations were more often located to the left. The separation between the groups was not complete, and some T and F observations were mixed together. How models predict the observed moisture content gradients in site T or F is shown in Table 1, and moisture content gradients corresponding to observations marked in the score plot can be seen in Fig. 6 and Fig. 7. The four observations were chosen to show examples of gradients from trees with different growing conditions—

FU suppressed tree in moist forestland,
FH dominant tree in moist forestland,
TU suppressed tree on dry sandy heath,
TH dominant tree on dry sandy heath.

As can be seen in Fig. 7, observations in the upper right quartile (A) have a high MC_{surf} with a rather steep gradient. Gradients in the lower right quartile (B) have a rather high MC_{surf} with a high capillary water height compared to (A). Observations from the upper left quartile (C) have a low MC_{surf} and a rather steep gradient. The score plot shows that (D) diverges from other samples, and the shape of the gradient is unique for this material. The score plot and moisture content gradients indicate that observations from the dry site generally have a lower MC_{surf} than the observations from the wet site.

TABLE 1–A matrix showing how well the models predict the moisture content gradients on the wet site (F) or the dry site (T) during absorption. Observed and predicted from work set (observations from test set in parentheses). Model information, number of model, principal component, R^2X (explained variance of X-data), R^2Y (explained variance of Y-data), Q^2 (predicted variance) were used.

Observed	Predicted		Model*				
	F	T	No.	PC	R^2X	R^2Y	Q^2
Heartwood 14 days							
F	20	7	1	2	0.867	0.324	0.187
T	6	22		76% predicted correctly			
Heartwood 7 days							
F	16	7	2	1	0.288	0.383	0.327
T	4	22		78% predicted correctly			
Heartwood 3 days							
F	16(2)	7(2)	3	1	0.318	0.311	0.210
T	4(1)	20(3)		77% predicted correctly			
Heartwood 1 day							
F	19(3)	1(2)	4	3	0.804	0.608	0.377
T	1(1)	24(3)		96% predicted correctly			
Sapwood 14 days							
F	21(4)	2(1)	5	3	0.944	0.57	0.501
T	2(0)	24(4)		92% predicted correctly			
Sapwood 7 days							
F	22(3)	2(1)	6	3	0.941	0.675	0.606
T	1(1)	25(3)		94% predicted correctly			
Sapwood 3 days							
F	25	7	7	2	0.883	0.527	0.334
T	5	20		79% predicted correctly			
Sapwood 1 day							
F	19(4)	3(0)	8	2	0.888	0.475	0.397
T	6(0)	20(4)		81% predicted correctly			

* Some observations were removed from statistical evaluation because of inaccurate repositioning of test objects, or knots in the measured area; one observation was removed because of wrong data, absorption for 3 days instead of 1 day.

Sorption in sapwood

The score plot for Model 5 absorption after 14 days in sapwood, shows that the observations on the dry site were more frequently located to the right and that observations on the wet site were to the left (*see* Fig. 8). Moisture content gradients corresponding to observations are marked in the score plot (*see* Fig. 9).

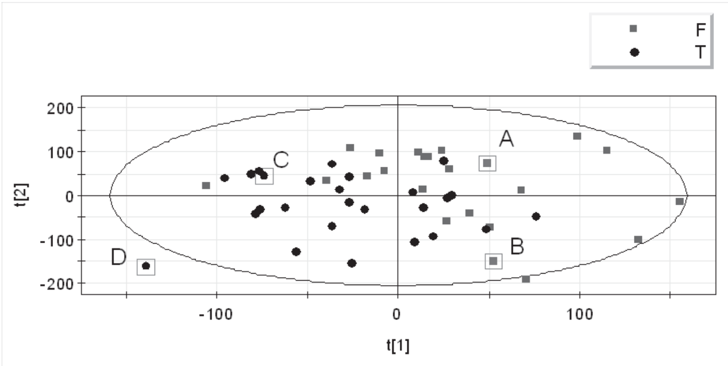

FIG. 6–Score plot for moisture content observations from the dry site (T) and the wet site (F) measured in heartwood after 14 days of absorption (Model 1). Moisture content gradients corresponding to observations are marked with rectangles.

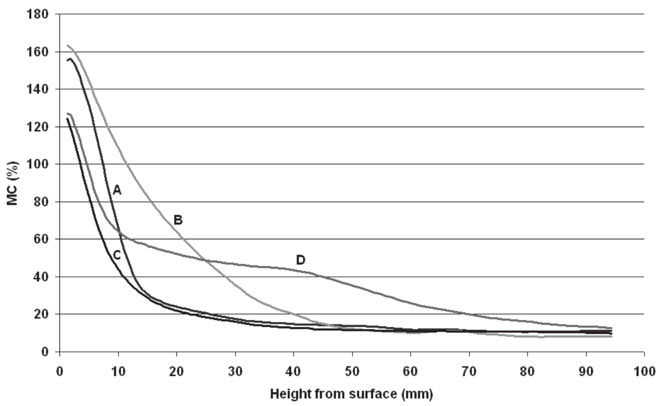

FIG.7–Moisture content gradients measured in heartwood after 14 days of sorption (*see* rectangles in Fig. 6). Observations from wet site/suppressed = A, wet site/dominant = B, dry site/suppressed = C, and dry site/dominant = D.

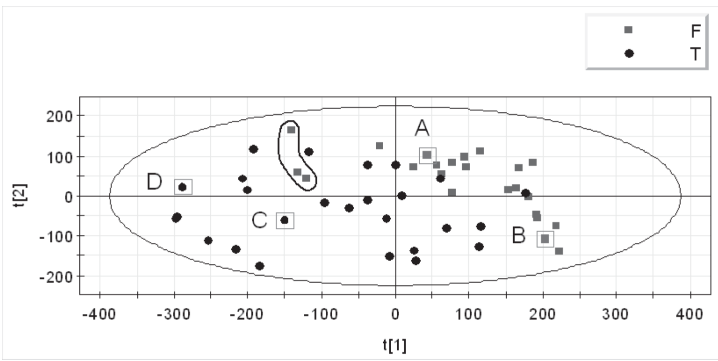

FIG. 8–To the left in score plot, observations from dry site (T) and to the right, observations from the wet site (F), after absorption for 14 days in sapwood (Model 5). Moisture content gradients corresponding to observations are marked with rectangles.

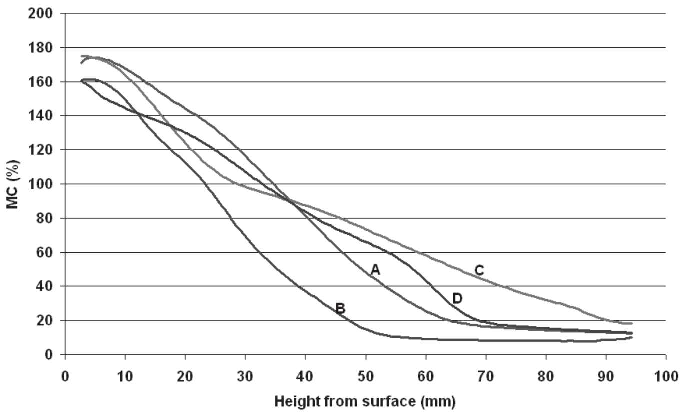

FIG. 9–Moisture content gradient in sapwood after absorption for 14 days in end grain marked in score plot (Fig. 8). Observations from A = wet site/dominant, B = wet site/dominant, C = dry site/dominant, and D = dry site/dominant.

The models classified the observed moisture content gradients as belonging to the dry or the wet site (Table 1). After sorption for 14 days, 76% of the heartwood observations and 92% of the sapwood observations were predicted correctly. The difference in moisture content gradients between the wet and the dry sites seems to be greater in sapwood than in heartwood. For example, in heartwood Model 1, 20 of the observations from the work set were predicted correctly as belonging to the moist forest site. Seven observations from the work set were predicted as the dry heath site.

There is no perfect separation between the classes. For example, wet-site observations from one tree were consistently located among the dry-site observations (Fig. 8) from all three heights and all periods of sorption in heartwood. The observations behaved in a similar way in sapwood and during desorption as well.

A single observation can have a rather large impact on the models in Table 1. If a moderate outlier was removed, predicted variance increased considerably. For example, a moderate outlier was removed from Model 3 and the model improved to $R^2X = 0.846$, $R^2Y = 0.586$, $Q^2 = 0.497$.

If the same test object was removed from Model 7, the model improved to $R^2X = 0.94$, $R^2Y = 0.556$, $Q^2 = 0.481$. One reason for this is the relatively small number of observations explaining the model. Observations that more frequently behaved strangely were found at Level 1 (0.8 m from butt cut).

Another divergent observation, D (Fig. 6 and 7), measured at Level 1, had a very special shape in heartwood. The shape appeared after 1 day of sorption and then became more intensified with time. The shape of the gradient was still visible during desorption (*see* gradient D in Fig. 10).

Desorption in heartwood

A score plot for desorption in heartwood for Model 10 after 3 days is shown in Fig. 11. Four observations marked in Fig. 11, and the corresponding moisture content gradients in Fig. 10, show the difference in gradients after drying for 3 days. B is one of the wet-site observations that were frequently grouped among the dry-site observations during absorption as well as desorption in Fig. 11.

Gradients B and C show the two most extreme moisture content gradients from the wet-site group. Gradient C in Fig. 10 has a high moisture content level and is far from being dried after desorption for 3 days, in comparison to B which has reached a moisture content level around 20%. The score plot and gradient plot indicate that the dry-site group observations reach a lower moisture content faster than the wet-site group in heartwood.

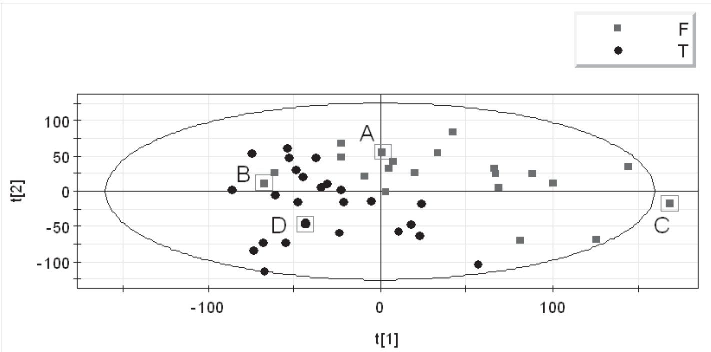

FIG. 10–Score plot for moisture content observations from the dry site (T) and the wet site (F) measured in heartwood after desorption for 3 days in room climate (Model 10). Moisture content gradients corresponding to observations are marked with rectangles.

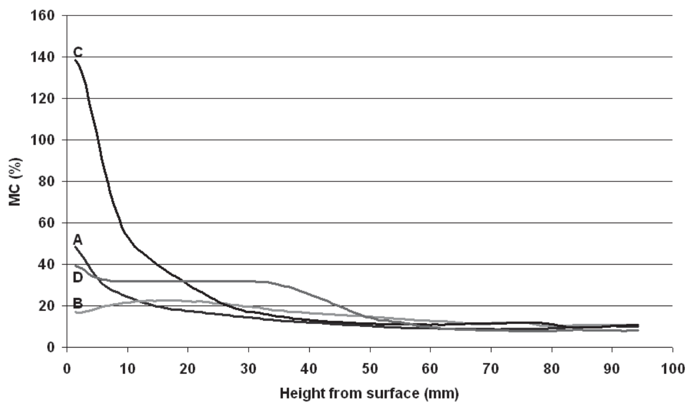

FIG. 11–Moisture content gradients in heartwood corresponding to observations marked with rectangles in Fig. 10 (A = wet site/suppressed, B = wet site/suppressed, C = wet site/dominant, and D = dry site/dominant).

Desorption in sapwood

In the score plot for Model 15 (*see* Fig. 12), wet-site observations group more frequently to the right and dry-site observations more frequently to the left. Two of the wet-site observations that were mentioned during sorption and desorption in heartwood still mix with the dry-site observations to the left.

Observation C is the same test object that had a large impact on Models 3 and 7 during absorption (in Table 1). Here it can be seen that even during desorption, the observations behave as outliers, and the gradients have rather high moisture content (*see* Fig. 10). The score plot and the moisture content gradients indicate that after 3 days of drying, none of the sapwood observations has reached a low moisture content level except the outlier to the left in Fig. 12.

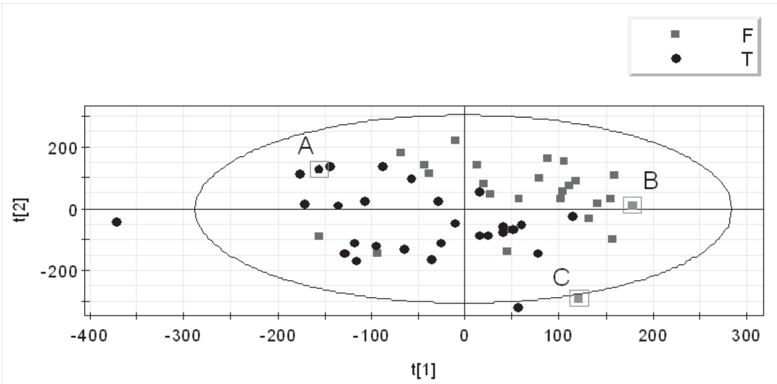

FIG. 12–Score plot (Model 15) after desorption for 3 days in sapwood (A = dry site/suppressed, B = wet site/dominant, C = wet site/dominant). Moisture content gradients corresponding to observations marked with rectangles are shown in Fig. 13.

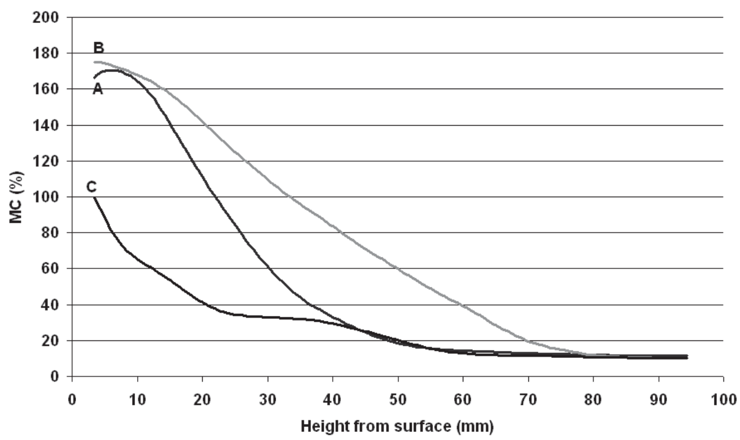

FIG. 13–Moisture content gradients in sapwood, corresponding to observations marked with rectangles in Fig. 12.

A matrix that shows how well the models predict the observations in wet and dry sites after desorption in room climate for 3, 4, and 5 days is given in Table 2. In the table, 3-4 shows that observations from Levels 3–4 have been used in the models and 1-4 indicates observations from all three heights. Most of the observations that

TABLE 2–A matrix showing how well the models predict the moisture content gradients into the wet site (F) or the dry site (T) during desorption. Observed and predicted from work set (observations from test set in parentheses). The designation 3–4 in the table indicates that observations from Levels 3 and 4 have been used in the models; the designation 1–4 indicates observations from all three heights in the tree.

Observed	Predicted		Model*				
	F	T	No.	PC	R^2X	R^2Y	Q^2
Heartwood 3 days, 3–4							
F	13(1)	0(1)	9	2	0.899	0.665	0.583
T	0(1)	1 (3)		100% predicted correctly			
Heartwood 3 days, 1–4							
F	20	6	10	2	0.89	0.529	0.487
T	1	28		87% predicted correctly			
Heartwood 4 days, 3–4							
F	10(3)	3(0)	11	2	0.883	0.408	0.172
T	2(1)	12(4)		82% predicted correctly			
Heartwood 5 days, 3–4							
F	9(4)	4(0)	12	2	0.677	0.511	0.302
T	2(0)	14(2)		79% predicted correctly			
Heartwood 5 days, 1–4							
F			13				
T				No model			
Sapwood 3 days, 3–4							
F	16(2)	0(0)	14	4	0.969	0.762	0.674
T	0(1)	19(0)		100% predicted correctly			
Sapwood 3 days, 1–4							
F	22(2)	3(0)	15	3	0.948	0.575	0.485
T	5(1)	23(1)		85% predicted correctly			
Sapwood 4 days, 3–4							
F	14(3)	0(1)	16	4	0.985	0.808	0.743
T	1(0)	15(4)		97% predicted correctly			
Sapwood 5 days, 1–4							
F	23(3)	3(1)	17	3	0.977	0.57	0.494
T	2(3)	20(1)		90% predicted correctly			

* Some observations were removed from the statistical evaluation because of inaccurate repositioning of test objects and knots in measured area.

behaved strangely were from Level 1, especially in heartwood. When Level 1 observations were removed, the models improved (*see* Table 2). Differences between wet and dry sites decreased with time and were most obvious after 3 days' desorption; at this point 100% of the observations from the work set were predicted correctly in both sapwood and heartwood when observations from Levels 3 and 4 were used. After 5 days' desorption in sapwood there seemed to be a notable difference between moisture content gradients from the wet site and the dry site, but in heartwood the difference was less obvious. When the wood dried, the moisture content gradients levelled out and became more similar to each other. As mentioned earlier, there are observations that systematically influence the models, and the models would improve if these were removed or if there had been more observations in the test that behaved in the same way.

Moisture content profiles measured with CT scanning at three heights

PLS-discriminant analysis was used to separate moisture content gradients according to different heights in the stem. Three classes were used: Level 1, Level 3, and Level 4.

Absorption in sapwood

It was not possible to separate moisture content gradients depending on heights within the trees. This indicates that there were no significant differences between moisture content gradients from different heights within the trees.

Absorption in heartwood

After absorption in heartwood for 14 days, Model 18 predicted 66% of observations correctly into Levels 1, 3, and 4 (Table 3). Level 1 was clearly different from Levels 3 and 4. Evidently, it was difficult to separate Levels 3 and 4 from each other. The differences in the height of the trees probably depend on the different heartwood properties, on compression wood, or on rot close to the root.

TABLE 3–The matrix shows how well Model 18 predicts the moisture content gradients into Levels 1, 3, and 4 during absorption in heartwood for 14 days. Observed and predicted from work set.

Observed	Predicted			Model				
14 days	Level 1	Level 3	Level 4	No.	PC	R^2X	R^2Y	Q^2
Level 1	18	1	0	18	3	0.935	0.33	0.192
Level 3	1	10	7					
Level 4	2	8	8		66% predicted correctly			

Desorption in heartwood

Observations from Level 1 were very well predicted into Level 1, but Levels 3 and 4 were more difficult to separate from each other (*see* Table 4).

TABLE 4–A matrix showing how well Model 19 predicts the moisture content gradients into Levels 1, 3, and 4 during desorption in heartwood for 3 days. Observed and predicted from work set (test set in parentheses).

Observed	Predicted			Model				
3 days	Level 1	Level 3	Level 4	No.	PC	R^2X	R^2Y	Q^2
Level 1	17(1)	1(0)	0(0)	19	3	0.944	0.363	0.292
Level 3	0(0)	10(2)	5(1)					
Level 4	1(0)	10(0)	4(2)	65% predicted correctly				

Desorption in sapwood

A PLS-discriminant analysis with three classes (Levels 1–3) gave no principal component. Evidently, there is no relationship between moisture content gradient and the height within the tree in sapwood.

Suppressed or dominant

It was not possible to separate moisture content gradients for absorption for 14 days in sapwood and desorption for 3 days in sapwood or heartwood. This indicates that there was no significant difference between the moisture content gradients that depended on whether the trees had grown suppressed or dominant

DISCUSSION AND CONCLUSIONS

The following conclusions can be drawn from the results obtained in this study:

- There is a great difference between gradients from sapwood and heartwood during capillary water sorption. The gradients from heartwood are steeper and return to nearly 12% moisture content much closer to the surface than those from sapwood.
- In sapwood, there is no difference in moisture content gradients during sorption or desorption with the height in the trees.
- In heartwood, there is a tendency toward a difference between moisture content gradients from the first log and the second log during absorption for 14 days and desorption for 3 days. The difference probably depends on differences in heartwood properties, reaction wood, or root rot close to the butt cut.

- Whether or not the trees have grown as dominant or as suppressed has no influence on moisture content gradient during sorption and desorption.
- Moisture content gradients from trees grown on the dry site had a different moisture content profile from the trees grown on the wet site.

It is possible to evaluate the totality of moisture content gradients with multivariate technique and thereby take into consideration all parameters (moisture content values) that have been measured as well as shape. It is important to prepare the data set and eliminate all extreme values that do not belong to the model (knots) and to replace these as missing values. Otherwise, the knots and other anomalies disturb the model and behave as outliers, weakening the model capability. Here, a small number of observations had a large impact on the models. This was probably due to the fact that there were relatively few test objects. Almost all the outliers or measurements that behaved strangely were taken 0.8 m from the butt cut. The results showed that measuring 0.8 m from the butt cut is perhaps too close to the cut, since the wood is not uniform, and the measurements can be affected by root rot and compression wood. Richter & Sell (1992) found that the variation in capillary water height was only marginal within the stem measured at 4, 8, 12, and 16 m over 24 hours. The largest difference in moisture content gradients, and thus water sorption, was found within the radius of the stem, i.e., between heartwood and sapwood.

Site factor probably depends on variations in the development of the wood structure depending on the trees' access to free ground water. The trees were taken from the same research park. They had grown under approximately the same climatic conditions (sun, snow, and rain), but the soil conditions and access to water had varied. The trees had about the same diameter, but the there were major differences in age and annual ring width between the slowly grown trees from the dry site and the faster grown trees from wet site. Moisture content gradients in sapwood were easier to predict on the wet site, and on the dry site those of heartwood were. This was probably because the wood structures become more similar to each other when heartwood formation starts; pit aspiration probably also plays an important role.

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