DOCTORAL THESIS

Norway Spruce Heartwood

Properties Related to Outdoor use

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LULEÅ UNIVERSITY OF TECHNOLOGY

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Abstract

Degradation of wood is a complex problem dependent on many parameters, but especially the presence of excessive amounts of water causes many problems.

The objective of this work was to study the influence of various parameters on water absorption and desorption in Norway spruce (*Picea abies* (L.) Karst). Focus has been on parameters that are measurable in the industrial chain and that affect liquid water absorption and desorption in end grain of Norway spruce. Most damage occurs in the end grain on products exposed outdoors, and this is often due to liquid water absorption.

Computed tomography (CT) scanning and image processing were used to measure liquid water in end grain for 1, 3, 7 and 14 days absorption and desorption in room climate. To ascertain whether the differences observed correspond to differences in microbiological activity and cracking, test objects were exposed outdoors aboveground for 5.5 years. For these studies, spruces were selected with a strategy to obtain as large differences as possible between parameters that could be expected to influence water distribution in the tree, such as crown size, density, age and access to water. All trees were selected from Vindelns Försöksparker (Vindeln's Research Site) in the north of Sweden.

The following are the most important findings from this study:

- Heartwood absorbs less water than sapwood and when dried in room climate reaches a dry level more rapidly than sapwood. Heartwood moisture content (MC) gradients were generally steeper, with lower moisture content than sapwood.
- After aboveground exposure for 5.5 years, heartwood panels had fewer cracks, shorter crack lengths and less growth of discoloration fungi on the undersides of the panels than sapwood.
- The MC gradients increase with time in a uniform way. The amount of water absorbed was expressible as a linear function of the square root of time.
- In the young spruces (37 years old), the border between sapwood and heartwood was less pronounced than in the older trees. There was an intermediate zone with MC gradients more similar to heartwood than to sapwood.
- In sapwood, there was no difference in MC gradient during absorption and desorption within the height of the tree. In heartwood, there was a tendency to differences in MC gradients from specimens 0.8 m from the butt cut compared to 5.8 and 9.5 m.
- When absorption and desorption cycles were repeated 3 times, moisture-content gradients in sapwood decreased from cycle 1 through cycles 2 and 3. In heartwood, the moisture content gradients followed almost the same curve for cycles 1, 2 and 3.
- Separation of sapwood and heartwood in dry state with near-infrared spectroscopy (NIRS) and multivariate analysis is possible. The visible-wavelength spectrum has a significant influence on the predictive power of separation models.
- Saw simulation has shown that it is possible to produce boards for outdoor cladding with 100% heartwood. However, the products have to be sawn from bigger logs than are normally used today. This has a negative effect on the yield, but this can be compensated for by extracting more side boards or by higher sales prices.

Keywords: absorption, desorption, CT scanning, near-infrared spectroscopy, durability, image processing, liquid water, spruce, heartwood content.

Sammanfattning

Nedbrytning av trä är ett komplext problem som beror på många parametrar, men speciellt inverkar fritt vatten, t.ex., från regn.

Målet med arbetet var att studera hur olika parametrar påverkar vattenupptagning och uttorkning i gran (*Picea abies* (L.) Karst). Fokus har legat på parametrar som är mätbara industriellt och som påverkar vattenupptagningen och uttorkningen i ändträ på gran. De flesta skador uppträder i ändträet på utomhusexponerat trä på grund av den snabba vattenupptagningen i längdriktningen.

Datortomografi användes för att studera vattenupptagningen. Bildbehandling användes för att mäta förändring under 1, 3, 7 och 14 dagars vattenupptagning och uttorkning i rumsklimat. För att undersöka om skillnader i vattenupptagning påverkar mikrobiell aktivitet och sprickbildning startades ett utomhusförsök ovan mark. Granarna till försöket valdes med en så bred spridning som möjligt av parametrar som kan förväntas påverka vattenupptagning, såsom trädens kronstorlek, densitet, ålder och framförallt tillgång på vatten. Alla träden togs från Vindelns försöksparker i Västerbotten.

Följande är de viktigaste rönen från denna studie:

- Kärnved suger upp mindre vatten än splintved och torkar snabbare i rumsklimat än splintved. Fuktkvotsgradienterna var generellt brantare, med lägre fuktkvot än de i splintved.
- Utomhusförsöket visade att efter 5,5 års exponering hade kärnved kortare spricklängd och färre sprickor än splintved och mindre påväxt av missfärgande svampar på undersidan av provbitarna än splintved.
- Fuktkvotsgradienterna ökade konstant med tiden och kunde uttryckas som en linjär funktion av kvadratroten av tiden.
- Det var ingen signifikant skillnad i fuktkvotsgradienter i splintved relativt höjden i stammen mätt på tre nivåer, 0,8, 5,8 och 9,5 m. För kärnved fanns det en viss skillnad i fuktkvotsgradient mellan rot- och mellanstock. Däremot var det ingen skillnad mellan 5,8 m och 9,5 m.
- Skillnaden i vattenupptagning mellan kärnved och splintved var mindre för de unga granarna (37 år) än för de äldre granarna. Det fanns en ”mellanzon” mellan kärnved och splintved där fuktkvotsgradienterna var mer lika kärnved än splintved.
- När uppfuktning och uttorkning upprepades i tre cykler minskade fuktkvotsgradienter i splintved från cykel 1 till cykel 2 och 3. I kärnved, å andra sidan, följde fuktkvotsgradienten nästan samma kurva all tre gångerna.
- NIR spektra och multivariat analys användes för att separera kärna och splint av gran i torrt tillstånd. Synliga våglängder hade en signifikant inverkan på modellerna.
- Sågsimulering visade att det är möjligt att producera bräder till utvändig beklädnad med 100% kärnved. Men produkterna måste sågas ur stockar med en större diameter än vad som är vanligt idag. Det har en negativ effekt på utbytet, men det kan kompenseras genom att fler sidobräder sågas ut eller genom ett högre pris.

Preface

The work presented in this thesis was carried out at SP Trätek, Technical Research Institute of Sweden and Luleå University of Technology (LTU), Division of Wood Technology, Skellefteå.

The project was financed by the SkeWood programme, through Norrskogs Forskningsstiftelse (NFS), Vinnova (Swedish Agency for Innovation Systems) and Swedish Forest Industries Federation (Wood mechanical section). A very special thanks to my contacts in the project reference group, professor Per-Owe Bäckström, Swedish University of Agricultural Sciences (SLU Umeå), Dr. Tomas Lundmark (Vindeln's Experimental Forest) and Olle Stendahl (NFS) and to professor Anders Grönlund (SkeWood) and Martin Gustafsson (Trätek) for their interest and support in the first part of the work.

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Skellefteå, May 2009.

Karin Sandberg

List of papers

This thesis is based on work reported in the following papers, referred to by roman numerals:

I. Sandberg K. (2002) Influences of growth site on different wood properties in spruce sap-/heartwood using CT-scanner measurements. In *Proceedings of the Fourth Workshop* Connection Between Forest Resources and Wood Quality: Modelling Approaches and Simulation Software*, Organized by IUFRO Working party S5.01-04* Harrison Hot Springs Resort Harrison Hot Springs, BC Canada, September 8–15, 2002.

II. Sandberg K. Lindgren O. (2003) Measurement of spruce moisture gradients using CT scanning during three cycles of liquid water absorption and desorption in end grain. In Proceedings of the Fifth International Conference on Image Processing and scanning of Wood, IWSS 5, organized by Joanneum Research Graz, Bad Waltersdorf, Austria, March 23–26, 2003.

III. Sandberg K. 2006. Modelling water sorption gradients in spruce wood using CT scanned data, New Zealand Journal of Forestry Science, Volume 36 No. 2/3 2006.

IV. Sandberg K. 2007. Moisture content gradients in young spruce during liquid water sorption in end grain measured with CT scanning, Proceedings from Nordic Workshop on Wood Engineering, Skellefteå February 21 2007, Woodtech Sweden, www.woodtech-swededen.org

V. Sandberg K. Salin J-G. 2009. Liquid water absorption in Norway spruce measured with CT scanning and viewed as a percolation process, Submitted to Wood Science and Technology 2009.

VI. Sandberg K (2008). Degradation of Norway spruce (Picea abies) heartwood and sapwood during 5.5 years' above-ground exposure, Wood Material Science & Engineering, Vol. 3. Nos. 3–4 2008.

VII. Sandberg K. Sterley M. 2009. Separating Norway spruce heartwood and sapwood in dried condition with near infrared spectroscopy (NIRS) and multivariate data analysis, accepted for publication in European Journal of Forestry Research.

VIII. Lundahl C.G. Sandberg K. Grönlund A. 2009. Production of heartwood Products-Effects on Volume Yield, submitted to Forest product journal 2009

Contribution to the included papers

Paper II: O. Lindgren contributed with supervision about CT scanning and comments on the text in the article.
Paper V: J-G Salin contributed with discussions, the structure of the paper, percolation simulations and wrote parts of the text in the article.
Paper VII: M. Sterley contributed with support regarding NIR measurements, multivariate analysis and comments on the text.
Paper VIII: K Sandberg contributed with research work, structure of the paper, discussions, wrote the introduction and some text and commented on the written article.

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1 Introduction

The degradation of wood is a complex problem dependent on many variables, but especially the presence of excessive amounts of water in wood causes many problems. First of all, fungi that cause decay or blue sap stain need water to live and propagate. Water also affects dimensional change through shrinking and swelling, which in turn influence crack formation and strength. Consequently, wood that naturally has low water-absorption ability should be desirable for outdoor use.

High durability and minimal maintenance are important for all building materials. These issues are especially in focus in the outdoor use of wood. Increasing costs for maintenance lead to a desire for raw material of consistently high quality. Consistent quality is important, because it is expensive to repaint or replace damaged components. In addition, the structure, the colour and, in the worst case, the dimensions may mismatch, necessitating the replacement of even greater amounts of material.

The performance of wood and its service life for products in exterior use above ground will be greatly affected by construction practices, maintenance and degrees of protection from prolonged wetting. Even wood with natural durability against microorganisms breaks down with an incorrect design. Good designs ensure that water easily rolls off and that no water is trapped in the construction. On the other hand, with a good design, less durable wood can last for a very long time. This can be seen in many old houses. For example, buildings can be provided with generous roof overhang to keep the walls and windows fairly dry and free from splash.

Durability is most often associated with biological resistance to decay. Nevertheless, for aboveground applications of wood, other aspects of durability can be equally important and also be a secondary influence on biological durability through, for example, form stability and cracks. Cracks tend to lead water into the wood and into the construction as a whole and thereby increase risk for decay and reduce strength. Decay is undesirable, of course, but in many aboveground constructions, it is a slow process, especially if good protection of the wood is built into the design. This makes it possible for the wood to dry out between wettings. Visible aesthetical factors such as cracks, raised fibres, discolouration and mould tend to reveal themselves much earlier than decay and are many times experienced as being equally troublesome. The choice of a material based solely on resistance to decay can result in a durable product, but if it develops a lot of cracks or becomes deformed, it will nonetheless not be a desirable product from the point of view of the consumer. The product may need to be replaced long before any decay appears.

Long ago, before forestry became industrialized, wood for buildings was selected based on knowledge of the differences in quality and function between the trees. To know if the wood was suitable, parameters such as crown size, bark features, stem properties, branches, site, colour of the wood, *etc.*, were considered in quality selection (Anon. 1985; Sjömar 1988). In fact, every piece of wood is unique with regard to structure and characteristics. Differences in structural behaviour in turn affect wood's physical behaviour (de Zeeuw 1965). That gives rise to trees with different features, and today we can use measurement techniques to select appropriate raw material, as in old times. But apart from requiring knowledge of measurement technique, it is necessary to know which parameters to use for sorting, and why.

1.1 Degradation

Surfaces exposed outdoors aboveground degrade as a result of exposure to such environmental factors as sunlight (visible and infrared radiation), moisture (dew, rain, snow), temperature, oxygen and atmospheric pollutants (Hon 1983). Under the influence of the factors named above, all wood material exhibits a loss in performance that can be called degradation. There are six groups of degradation according to Desh & Dinwoodie (1996), biological (fungal and insect attack), chemical, photodegradation, thermal, fire and mechanical.

A number of researchers have studied the degradation of wood surfaces with different points of departure. Studies have been done involving, for example, the influence of ultraviolet radiation and colour changes, microscopic examination of checks and anatomical changes, surface treatment, biological degradation and accelerated weathering.

Degradation or deterioration of wood during outdoor exposure is a complex combination of biotic, chemical and physical agents acting alone or in combination (Zabel & Morrell 1992). Degradation is here divided into the categories of weathering and decay. Weathering is a surface degradation that has little effect on strength properties and is caused primarily by photochemical damage, oxidation of breakdown products, leaching of soluble decomposition products, hydrolysis, mechanical damage from shrinkage and swelling and discolouration by blue-staining fungi. In decay, or biological destruction, microorganisms participate, the entire thickness of the wood can be affected and strength can be reduced considerably. Weathering is a slow process compared to decay, which can destroy wood in just a few years if conditions are favourable to the fungi and free water is available in the wood cells (Feist 1982; Zabel & Morrell 1992; Rowell 2005).

Weathering

Unprotected wood surfaces exposed to weather undergo changes in colour and structure. First, the surface usually changes to a brown colour. After some time, a thin silvery grey layer 0.08–0.2 mm thick (Browne 1960) arises when rain leaches products of decomposed lignin and leaves the fibres of cellulose. The thin, silvery grey surface absorbs and reflects chemically active ultraviolet and visible light and protects the surface from photochemical reactions and further breakdown processes (Borgin 1971). Substance loss at the surface is rather slow, about 5–6 mm over 100 years, and varies in depth between 1 mm and 6 mm within a 100-year span (Browne 1960; Feist 1982).

Greying on wood in the presence of moisture is practically always due to growth of blue-staining fungi such as *Aureobasidium pullulans* on the surface of the wood (Sell 1968; Sell & Wälchli 1969; Kühne *et al.* 1970; Sell & Leukens 1971). In the absence of blue-staining fungi, the surface becomes more white than grey (Sell & Wälchli 1969).

During exposure, the wood surface will also break down mechanically through deformation during hygroscopic and thermal movements that cause shrinking and swelling. The surfaces become rough and develop cracks, latewood grain rises above earlywood, the surface erodes and the cracks increase in size and number as long as degradation of the surfaces continues.

Decay

Major types of wood biodeterioration are decay and/or discolorations. Mould and blue stain fungi are often called discolouration fungi and are often initial microbial colonizers of wood. The stain fungi that invade parenchymatous tissues in sapwood produce masses of pigmented hyphae in wood cells, which results in the discolouration. Staining fungi cause little damage, but increase the permeability of wood (Zabel & Morell 1992).

Decay is caused by decay fungi that grow through the wood cells and release enzymes that break down the wood components that they metabolize as food (Rowell 2005). Since decay is caused by fungi that digest wood, it results in loss or significant reduction of many wood properties, such as toughness and strength.

The succession of microorganisms in the decaying of wood is very complex and variable. Different fungi need different conditions in terms of nutrients, temperature and moisture in order to establish themselves on wood and survive, and existing fungi may determine the subsequent succession of fungi that colonize the wood (Findlay 1965; Scheffer 1973). The structural constituents of wood species as well as chemical composition and type and amount of extractives influence the rate of decay from particular decay fungi (Scheffer & Cowling 1966; Winandy & Morrell 1993). Since growth conditions such as availability of nutrients and water are different above the ground and in the ground, the development of decay differs in aboveground and in-ground situations. The breaking-down process is faster in the ground than aboveground.

During decay, the wood changes chemically. These changes manifest as visible discolouration and texture changes as the breakdown proceeds, depending on the types of attacking fungi and the stages of decay. Various groups of fungi attack the wood cell-wall constituents in different ways, and that results in several types of decay. Most common are white-brown and soft rot degradation. Based on the visible changes in wood, various methods for detecting and evaluating decay have been developed. Methods in common use today for evaluating wood durability are visual evaluation, image analysis, microscopic evaluation, pick or splinter test, density and mass loss and strength test (Råberg *et al.* 2005).

The standard EN 350-1 puts the natural durability of wood into five classes, where 1 is very durable and 5 is perishable. Classification is determined in the field using specimens in ground contact according to EN 252 for at least 5 years or in a laboratory according to EN 113, which involves decay fungi over a period of approximately 16 weeks. These are rather tough testing methods, since the fungi have optimal growing conditions during testing. The field test is evaluated as average life based on visual evaluation and pick test. The laboratory test is evaluated as mass loss. For aboveground applications, there are no principles for classification of natural durability according to EN 350-1. According to EN 350-2, spruce is slightly durable (class 4) in ground contact.

Spruce has been treated as a homogeneous material and has therefore seldom been separated into heartwood and sapwood. Thus, durability testing of spruce separated into heartwood and sapwood has been limited. Hirmke *et al.* (1998) investigated resistance to decay fungi according to the European standard EN 113 and found no difference between heartwood and sapwood of spruce. In contrast to this, a longer average life for spruce heartwood than sapwood in ground contact was found by Bergman and Mazur (1982).

In Sweden, it has been generally recognized that spruce is less sensitive to discolouring growths than pine is. Two studies support this view. Lagerberg *et al.* (1927) tested 10 fungi on sapwood from young trees of spruce and pine and found less blue-stain fungus growth on spruce than on pine. This has also been observed during drying of wood. Three thermotolerant species of fungus were inoculated onto fresh timbers that were subsequently dried at high temperature (Esping *et al.* 1981). The tendency toward fungal growth was somewhat more than twice as great for pine as it was for spruce under the same climatic conditions. Mainly sapwood was used in the tests.

Vittanen (1996) has studied mould growth on pine and spruce sapwood and found that spruce had slightly slower mould growth than pine sapwood. However, no significant difference in resistance to mould growth could be affirmed due to variations in the surface quality within the species.

1.2 Water, wood and degradation

Factors for the survival and growth of wood-inhabiting fungi are water, oxygen, temperature, digestible substrate, PH range and chemical growth factors (nitrogen compounds, vitamins, *etc.*). The major risk factor for timber exposed to weather is water, since water serves a variety of functions in the degradation process. Most of all, water is a prerequisite for decay and sap stain fungi, since they need free water (above fibre saturation point) in the wood cells in order to grow. The presence of water accelerates the weathering process by causing splitting and cracking, since the wetting and drying causes stresses in the wood when wood swells and shrinks. Water is also a medium for diffusion of both enzymes and wood degradation products (Rowell 2005, Feist 1982, Zabel & Morrell 1992).

Mould fungi have generally lower humidity and temperature requirements and grow faster than decay fungi. Generally, one could say that the optimal MC for wood-rotting fungi is between 40% and 80% in the wood, and the optimal temperature is between 25°C and 32°C, but they can withstand longer or shorter periods of dryness (Carling *et al.* 1984). Limitation of available water is the most important factor for the durability of wood. However, there is a risk of biological decay through the whole MC range from about 20% to approximately 100%. An accepted rule of thumb is that decay will not occur in wood with an MC below 20%, based on decay control in wood in use in protected environment with an added safety factor (Zabel & Morrell 1992).

Often, damage caused by water to outdoor wood products, such as windows and panels, occurs close to the end grain and joints (Holbrow *et al.* 1972; Gaby & Duff 1978; Sell 1982; Grönlund *et al.* 1983; Miller *et al.* 1987). This is mainly because of the rapid longitudinal transport of liquid water in the wood structure. Therefore it is important to protect the end grain by painting, and the surface treatment must be done prior to assembly on exterior applications aboveground. A number of investigations show the importance of protection of end grain with sealers and paint to reduce moisture uptake (Sell 1982; Öqvist 1988; Boxhall *et al.* 1992; Elowson *et al.* 2003). However, after some years' exposure, the initial effect of protective coatings has declined for sapwood. Generally, paint cannot make sapwood as durable as heartwood (Boxhall *et al.* 1992; Rydell *et al.* 2005).

The transport of water in wood can be divided into the two main categories of hygroscopic and capillary water transport. Hygroscopic transport is by diffusion of two types: intergas diffusion and bound water diffusion. Intergas diffusion involves the transfer of water vapour through the air in cell cavities (lumina) of cells. Bound water diffusion takes place within the cell walls of wood (Siau 1984). When the relative humidity is close to 100%, the cell walls of wood are saturated with moisture, a condition called the fibre saturation point (FSP). In this state, a moisture content of 28%–30% is generally assumed. Above FSP, capillary transport involves the passage of fluids through the interconnected voids, lumina in tracheids and through bordered pits of the wood structure under the influence of static or capillary pressure gradients (Siau 1984).

1.3 Liquid water transport in wood

In softwoods, the major transport flows longitudinally via hollow tracheids connected with small openings called pits. Most of the water is transported in earlywood tracheids with thin walls and large cell cavities. Latewood tracheids have thick walls and small cell cavities. The radial transport goes via horizontal ray tracheids that go from the pith to the bark. Tangential transport takes place via bordered pits connecting the radial walls in the closest tracheids. Liquid can be further transported via pith-ray tracheids to the vertical tracheids through very small bordered pits.

In dry softwood, it has been found that the primary pathway for axial flow is in longitudinal tracheids through bordered pit pairs (Wardrop & Davies 1961; Stamm 1967; Côté & Krahmer 1962; Richter & Sell 1992). In spruce, there is limited radial penetration due to the relatively small proportion of ray tracheids, which are regarded as the main radial pathways (Liese & Bauch 1967b; Nyrén & Back 1960). The ray tracheids in spruce are also often interrupted by parenchyma cells at the junction of the annual ring, and the latewood tracheids are about half as long as the earlywood tracheids, which may explain why penetration often stops abruptly at a particular annual ring (Liese & Bauch 1967b).

The number of pits per tracheid varies from 50 to 300 in earlywood to fewer in latewood, and the pits are concentrated mostly on the radial surface and in the overlap in the end of the fibres (Stamm 1946). In dry softwood, nearly all the earlywood bordered pits are aspirated, *i.e.*, are closed, blocking the flow. However, a substantial number of the latewood pits remain unaspirated (Phillips 1933; Liese & Bauch 1967a; Wardrops & Davies 1961; Petty 1972). This difference in behaviour of the pits is usually attributed to greater rigidity of the pit membranes and the greater cell-wall thickness found in latewood (Phillips 1933; Comstock & Côté 1968). It has also been reported that after drying, 50% of pine latewood remains open, but only 25% of spruce latewood (Liese & Bauch 1967a).

1.4 From sapwood to heartwood

Sapwood conducts sap to the cambium and crown and can act as a reservoir for storage of nutrients. When the whole cross-section of the stem isn't needed for water transport, the interior of the sapwood in the stem is transformed into heartwood. During the formation of heartwood, the chemical composition of the wood changes, and nutrients are transformed into defensive substances such as heartwood phenols and extractives. Transport of water and nutrients is stopped due to the bordered pits becoming aspirated, and as a result, the parenchyma cells die. Considerable research has been done on heartwood, with ensuing theories about the mechanisms of formation, properties, *etc*. Reviews of this area of research have been published by Bamber (1976), Hillis (1987) and Taylor *et al.* (2002).

Intermediate wood
The transition zone often contains living cells, but is devoid of starch (Hillis 1987). Intermediate wood is defined as “Inner layers of the sapwood that are transitional between sapwood and heartwood in colour and general character” (Anon. 1957). Intermediate wood can be confused with the narrow transition zone, and the terms have been used interchangeably. The intermediate zone of *Picea abies* is of variable width, sometimes up to 5–10 cm in a log cross-section (Hillis 1987). The moisture content in the intermediate zone is lower than that of sapwood and is similar to that of heartwood. It is uncertain whether all intermediate wood contains living cells (Hillis 1987).

1.5 Detection of heartwood of spruce

Nondestructive measurements
In most types of wood, when heartwood is formed, it becomes darker in colour than the surrounding sapwood. In spruce, that colour change doesn’t occur. Therefore it is difficult to separate Norway spruce heartwood from sapwood with the naked eye in dry state. The surest way to tell spruce heartwood and sapwood apart is to determine the presence or absence of living cells and/or starch in the wood. Living cells are found only in sapwood. Starch is not found in heartwood, but its absence cannot be taken as proof that heartwood has formed, since starch can appear on one side of a tree and not on the other due to seasonal variation (Chattaway 1952). A way of ascertaining the presence of heartwood in spruce is to measure the difference in moisture content between heartwood and sapwood, since heartwood has lower moisture content than sapwood as a result of heartwood formation. The average moisture content for spruce heartwood is between 34% and 40%; for spruce sapwood, the range is between 113% and 153%.

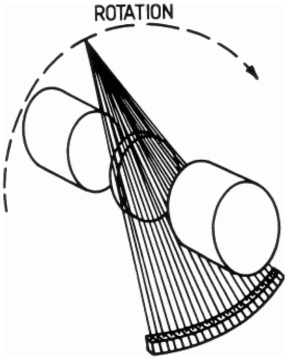
Various methods have been used to delineate sapwood and heartwood in green wood. Münster-Swendsen (1987) tried four methods: differences in natural colours, differential translucence, use of an aniline pencil and application of methyl red dye. The differential translucence method, in which thin cross-sectional discs are held up to the sky and the border is marked with a pencil, proved to be the best method. These methods are not practical in industrial use, and therefore nondestructive methods such as scanning with ionizing radiation (x-rays and γ-rays) or heat-sensitive infrared imaging have to be used. These methods rely on the differences in moisture content between heartwood and sapwood in order to separate the two types of wood.

Near-infrared spectroscopy
Near-infrared spectroscopy (NIRS) is a nondestructive method used in many applications for agricultural products, agro forestry, gases, food, beverages, wool, textiles, petrochemicals, polymers, pharmaceutical and biomedical, *etc*. NIRS is a technique for measuring transmitted or reflected light of wavelengths between 750 and 3000 nm. The NIR region is positioned between the visual and infrared regions of the light spectrum. In these wavelengths, most organic material has defined reflectance or transmittance. NIRS deals with organic molecules and requires samples that contain bonds such as C-H, N-H or O-H with a concentration of the analyte that exceeds 0.1% of the total composition (Burns & Ciurczak 2008).

CT scanning and imaging of wood
Computer tomography (CT) scanning is a nondestructive test method used in many applications in wood research. It has been used for density measurement, detection of

properties of sawn logs, such as knot parameters, strength properties, compression wood and spiral grain, and for the study of water absorption and drying.

The principle for CT scanning involves an X-ray tube and a detector array that rotate around the object being examined. The transmitted X rays are attenuated in the object and detected by the array of detectors opposite the source (Figure 1).



a

b

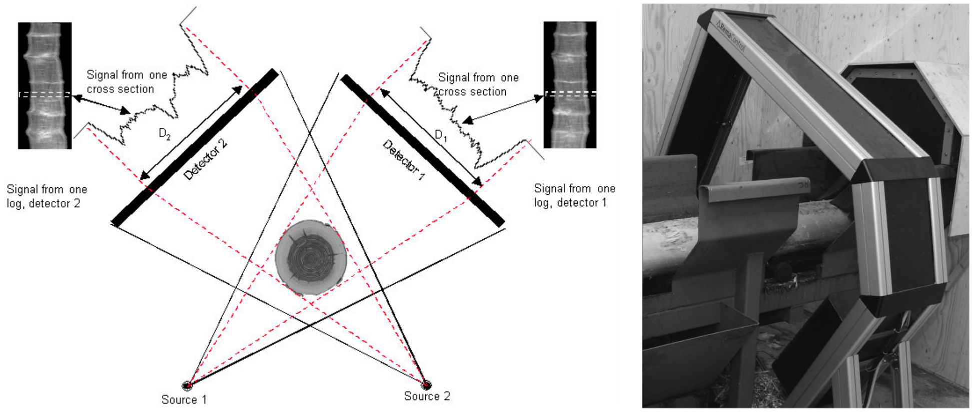
Figure 1. a) Principle of rotating X-ray tube and array detector (Lindgren 1991). b) Photo of a CT scanner.

When the X-ray tube and the detector array have rotated around the object, a large number of measurements of the X rays' absorption are acquired. These values are then used to construct an image of the object using mathematical algorithms. The image that is created describes the density variations in the cross-section, and with image processing, measurements can be executed in the images (Bucur 2003).

X-ray log scanner

Since CT scanning is too slow for industrial applications, industrial X-ray scanners have been developed. These scanners are designed with a limited number of fixed measurement directions (Grundberg & Grönlund 1997). Figure 2a shows the principle of a two-directional X-ray log scanner with two X-ray sources and two detector arrays. The signals from the detectors are analysed with image processing and multivariate statistical techniques. Industrial X-ray log scanners can measure log characteristics such as outer shape, knot structure, log type, annual ring width, distance between whorls, strength and heartwood content (Oja *et al.* 1998; Grundberg & Grönlund 1998; Skog & Oja 2009).

Today, X-ray log scanners are used at several sawmills as a process control tool that enables sawmills to achieve a customer-oriented production (Figure 2b).



a) b)

Figure 2. Schematic description of an X-ray log scanner with two measurement directions. (Grundberg & Grönlund, 1997) b) Log scanner at a sawmill (RemaLog X-ray scanner).

1.6 Aim and direction

The ambition was to find wood with qualities suitable for outdoor use above ground. The hypothesis was that differences in water absorption and desorption in the end grain cause differences in durability of building products.

Damage due to rot or cracking on constructions commonly occurs in the end grain close to the surface or sometimes a distance into the wood. Therefore it is important that wood should not absorb capillary water in the end grain and that it has the capacity to dry out during favourable weather conditions. For that reason, absorption and desorption in end grain were studied.

The trees used in this experiment were chosen to provide large differences in the parameters that can influence water distribution in the tree, such as the size of the crown and availability of water at the site.

1.7 Objectives

The objective of this work was to study the influence of various parameters on water absorption and desorption in Norway spruce with focus on parameters that are measurable in the industrial chain from the cutting of the tree to the sawing operation.

- In Paper I, CT scanning and image processing were used to measure water distribution during liquid absorption in end grain for 1, 3, 7 and 14–15 days and during drying in room climate. The objectives were to study water distribution within the radius of spruce, measure how far from the end grain the water could be transported, determine the heartwood content and investigate if there were any differences in absorption if the test objects were standing with butt end down or butt end up.
- In Paper II, moisture content (MC) gradients were investigated during liquid water absorption for 1, 3, 7 and 14–15 days in end grain and during drying in room climate repeated 3 times. The purpose was to determine whether the MC stayed the same, increased or decreased between the cycles.

- In Paper III, moisture content (MC) gradients were investigated during liquid water absorption for 1, 3, 7 and 14 days in end grain and drying in room climate. The objective of Paper III was to investigate weather MC gradients differed depending on the height in the tree and the growing sites.
- In Paper IV, MC gradients were measured in end grain during liquid water absorption for 1, 3, 7 and 14 days and during desorption in room climate. The objective was to find out if there is a difference in absorption and desorption between sapwood, heartwood and intermediate wood in young spruces from irrigated and control sites with a view to determining if young spruces have appropriate properties for use in exterior products.
- In Paper V, the objective was to compare simulations of liquid water absorption in wood as a fibre network and percolation with MC gradients during absorption in the longitudinal direction.
- In Paper VI, parameters important for the wood user were studied with regard to microbiological activity and cracking during outdoor aboveground exposure. Visual evaluation was used to study the number and length of cracks as well as surface change and discolouration. The purpose of this work was to study heartwood and sapwood of spruce during outdoor exposure aboveground in order to verify whether or not the differences in water absorption and desorption measured with CT scanning correspond to differences in microbiological activity and cracking during exposure outdoors.
- In Paper VII, the objective was to investigate if near-infrared spectroscopy (NIRS) together with multivariate data analysis can be used as a method to separate heartwood and sapwood in dry state.
- In Paper VIII, saw-simulation techniques combined with detailed information from 750 logs in the Spruce Stem Bank was used to investigate the effects on volume yield in production of high-heartwood-content products (panels). The objective of this study was to evaluate the prerequisites to minimize loss of volume yield during production of three given products from Norway spruce heartwood.

1.8 Limitations and error sources

In this study, all sample trees were taken from three sites within Vindeln’s research forest.

Error sources

One of the major problems involved in measuring the same test object many time is to ensure that the measurements are made in same position every time. To reposition the test object during CT scanning, drilled holes and marks on the surfaces were used as targets for a laser from the tomograph. Small mistakes in repositioning showed up as moisture content level far from the conditioned 12%, and the measurement was not usable.

To transform a CT value into moisture content, a geometrical transform of images must be done in such a way that cross-sections after test will appear identical to the reference image. The accuracy of the whole process of sampling two images, applying the algorithm for calculation of MC and subtraction of test image from reference image (oven dry) was tested on objects with an MC of 12%. Calculation of moisture content on conditioned test objects showed an average MC of 11.8% (s. d. 0.6), which indicates a good accuracy of measurement and transformation algorithms on larger volumes and when density variation is small.

The definitions of heartwood and sapwood were based on the differences in density (greyscale) in images. In a few test objects, the borders between sapwood and heartwood were difficult to define due to the presence of knots close to the surface and insufficient differences in the greyscale.

2. Materials and methods

2.1 Wood samples

The trees used in this experiment were chosen to provide large differences in the parameters that can influence water distribution in the tree, such as the size of the crown, wood density and availability of water at site. Twenty trees of Norway spruce (*Picea abies* (L). Karst.) were taken from a forest research site close to Vindeln in northeast Sweden (Lat. 64° 13′ N, Long. 19° 41′ E). One site, *moist forest*, had a good supply of water (wet), and the other site, *sandy heath*, was without free ground water (dry) (Papers I–III and Papers V–VII). Half of the trees had grown suppressed and half of them dominant. Altogether there were 5 trees in each test group.

One year later, the project was enlarged by ten trees, five that had been irrigated with water and fertilizer for 15 years (I) and five trees from a control site without irrigation (C) (Paper IV and Paper VII).

The logs were sawn through and through in north-south direction to 32-mm-thick boards and dried to 12% MC (Figure 3). The drying was performed with 60°C wet bulb temperature and maximum temperature of 80°C during the drying phase. The process was finished with steam conditioning at 90°C. The total drying time was 84 hours. Thereafter they were in a conditioning chamber for more than two months.

Specimens for different tests were taken from the logs in accordance with Figure 3. The measurements were performed in room climate. CT scans were performed after 1, 3, 7 and 14–15 days of liquid water absorption in end grain and during desorption, *i.e.*, drying, in room climate (Papers I–V).

Stem discs 5 cm thick were used to measure heartwood content, growth-ring width and age. Test objects for NIRS measurements (Paper VII) were taken from the stem discs.

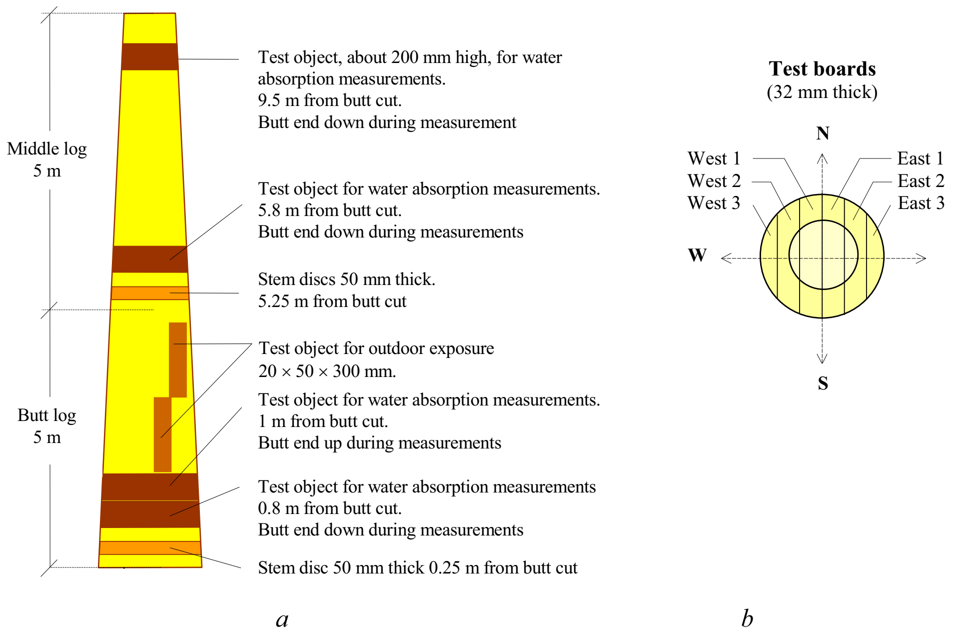


Figure 3.a) Sketches showing the locations where the test objects were taken in the trees. b) Sawing pattern.

For the outdoor exposure aboveground (Paper VI), test objects were taken 1.2 m and 1.5 m from the butt cuts of the logs. These were separated into heartwood and sapwood, half of which were painted with latex paint and half of which were left untreated.

2.2 Field test—above ground exposure

Specimens were placed outdoors in Skellefteå, Sweden, (Lat 64° 45′ N, Long 20° 56′ E) on 16 May 2002, in a horizontal position one meter above the ground with the tangential pith side upwards (Figure 4), resting on four screw heads with a distance of 5 mm to the support in order to avoid surface contamination (Paper VI). The test specimens were fastened with a string to avoid cracks arising from fastenings. Horizontal exposure was chosen in order to leave water and snow on the surface and expose the cross-sections of the specimens. A horizontal exposure (0°) maximizes the levels of ultraviolet radiation and weight loss (Evans 1989). Half of the test specimens were painted with white acrylic latex paint, 180 g/m^2, corresponding to a 60-µm-thick coating. No primer coat was used. The same treatment was used to seal the end grain. This method of treatment was chosen in order to speed up results obtained on the painted surfaces. The unexposed lower surfaces of the specimens were left untreated.

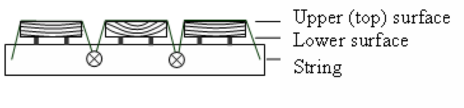


Figure 4. The test objects lying on four screw heads with a distance of 5 mm to the support, fastened with a string to avoid the influence of fastenings.

Microbiological activity and cracking, criteria important to the wood user, were studied. Both the upper and lower surfaces of the test pieces were examined. The following parameters were investigated: weight, crack length, number of cracks on upper and lower side, visual estimation of the growth of fungus on underside, visual appearance on upper side and microscopic analysis. Inspection and visual evaluation were performed after 3–5 five days of dry weather so that no rainwater or snow lay on the surfaces. The surfaces were not cleaned before examination.

Cracks
A steel ruler, a thickness gauge and a loupe were used to determine number and length of cracks on the upper and lower surfaces of the test pieces. Cracks with a width less than 0.2 mm and cracks in knots were not counted. If two cracks coincided, they were counted as one.

Visual evaluation
Discolouration due to fungus growth on the lower surfaces and weathering changes to the upper surfaces and end grain were estimated by visual evaluation. There were differences in the discolouration of the wood depending on whether the upper surfaces were untreated or painted; thus, these categories are taken up separately. The test objects were placed in falling order, ranked into three groups (see Table 2 in Paper VI). Then photos were taken and the test objects were evaluated to get a mean score for heartwood and sapwood. Cracks with a width between 0.2 and 0.4 mm were considered small, cracks with a width between 0.4 and 0.8 mm were considered medium and cracks wider than 0.8 mm were considered large.

Microscopic analysis
To determine the types of fungi, small specimens were analysed by microscope. Microscopic analyses were done twice, once in 2005 and again in 2007. Small samples for microscopic analysis were cut with a wood chisel after examination with a loupe so different kinds of growths could be detected. In 2005, 14 test objects were analysed under the microscope. In 2007, the lower surfaces of all untreated specimens, as well as five upper surfaces and five end grains from untreated specimens were subjected to microscopic analysis.

2.3 Measuring water absorption with CT scanning and image processing

Water absorption, wood density and moisture content were measured by CT scanning and image processing.

By taking a CT image at a certain unknown moisture content and subtracting it from a reference image at a known moisture content of the object, the unknown moisture content can be determined. In this case, the reference level was obtained after the test objects had been oven-dried at 103°C. The difference in CT number in each pixel will then be due to the presence of water. For this to work, the images must be geometrically transformed into the same size, since wood swells during absorption. For image processing, software from Scion Image was used (Scion Corporation 2004). The 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 developed in house. Moisture content was calculated according to algorithms developed by Lindgren (1992) (Papers I–V).

The amount of water was measured in two ways. In Paper I, *height* of water uptake was defined as an MC ≥ 40%. Areas with high water uptake were measured by threshold of digital images into two levels—white and black (see Figure 5).

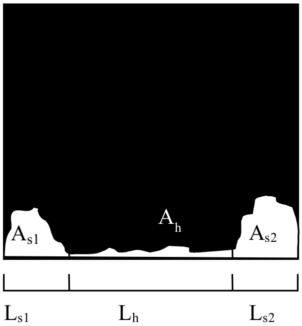


Figure 5. Threshold CT image showing water absorption in end grain of a spruce specimen. White areas correspond to wood that has an MC ≥ 40%. Black corresponds to areas with an MC less than 40%.

The average capillary water height (CWH) in sapwood ($S_{average}$) and in heartwood (H) was calculated according to Eq. 1 and 2.

$$S_{average} = \frac{\left(\frac{A_{s1}}{L_{s1}} + \frac{A_{s2}}{L_{s2}}\right)}{2} \tag{1}$$

$$H = \frac{A_h}{L_h} \tag{2}$$

In Papers II–V, MC gradients were used for measuring water absorption and desorption. The CT image in Figure 6 shows absorption after 14 days in water. The measurements were performed on sapwood and heartwood, mainly on the south side of the stem (to the left in the images). The MC gradients were measured in a volume element, W × t × (n × h) in Figure 6, where W_s and W_h are the width of sapwood and heartwood. The scan thickness, t, is 10 mm in the middle of the test specimen; h is the height of the pixel, ca 0.7 mm; n is the number of pixels vertically. The MC gradient is comprised of the MC values of the volume element W × t × (n × h) in each position from h1 up to the reference point 100 mm from the end-grain surface.

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. To ensure that the measurements were done at the same position, reference marks were used (R). The first two pixels (approx. 1.4 mm) close to the bottom edge were removed from the MC gradient in order to eliminate artefacts.

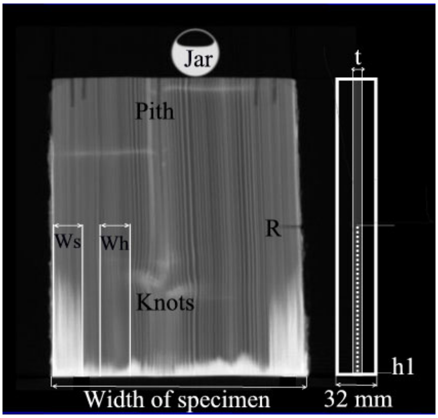


Figure 6. CT image of a vertical cross-section showing absorption after 14 days in water. Ws and Wh show where the gradients are measured in sapwood and heartwood. The gradients in heartwood are measured 12 mm from the sapwood borderline. R is a reference point 100 mm from the end-grain surface. On the top is a jar containing water as a density reference. t = 10 mm is the scan thickness, and h is the height of the pixel. h1 is the first pixel in the MC gadient up to 100 mm from the end-grain surface.

The capillary water height (CWH) used in Paper I shows only a single value for a particular moisture content level. The entire MC gradient has more information about the absorption and desorption process; therefore the MC gradients were used.

2.4 Fibre level modelling using a percolation approach

Percolation theory, an extensive mathematical model of percolation, is a way of modelling complex interaction in multifaceted systems and has been used for simulation the colonization of continents, the flow of electricity, forest fires, the movement of petroleum through fractured rock, kiln drying of wood over FSP etc (Wikipedia) (Salin 2006a, Salin 2006b)

Modelling water transport in wood as a fibre network makes it possible to consider the interaction between the capillaries and wood as a nonhomogeneous material. This is an improvement over the traditional approach of modelling absorption of liquid water in wood, which usually views it as a diffusion process in a homogeneous (but nonisotropic) material.

Salin (2008) has developed a model describing absorption of water in the capillary network formed by the fibres in the longitudinal direction in softwood. The fibre network structure in the longitudinal-tangential (L-T) plane describing the fibre cross-section has a highly elongated hexagonal form with overlapping fibre ends in the longitudinal direction. Most of the bordered pits are located at these overlapping surfaces. A rectangular fibre cross-section is assumed for the two other principal planes. To give a realistic result, stochastic variation in fibre size and other properties has to be included in the model (Salin 2008).

The percolation approach in the case of water absorption in wood means that 'wood' is not seen as a continuous medium, but as a material consisting of discrete parts – fibres, or tracheids – that interact with each other. These discrete parts are not identical, but each part is given individual properties according to stochastic distributions. Such stochastic variables are in this case the lumen diameter and the number of open (not aspirated) bordered pits between adjacent fibres. Such a discrete and stochastic model seems to capture several features seen in reality at the macroscopic level. The price is a tremendously increased calculation time compared to a continuous model, as the discrete parts have to be handled individually.

According to the model, in absorption of water in the longitudinal direction (Paper V), the driving force is the capillary suction created by the meniscus in the fibre lumen. This causes a flow of water into that lumen from adjacent fibres through tiny openings (bordered pits). It is assumed that all flow resistance is concentrated in these openings. The lumen diameter—and thus the capillary suction—is a stochastic variable in the model, and the average diameter also varies across the annual ring.

In this work it has been assumed that each fibre has 100 bordered pits and that these are aspirated with the probability p. Stochasticity in this respect is thus also included in the model. Values for p in the range 95%–98.5 % have been studied. For p = 96%, *i.e.*, an open structure, almost all fibres (≈97%) are eventually filled with water. For p = 98.5%, *i.e.*, a closed structure, all flow paths will eventually reach a dead end, and the absorption will stop.

2.5 Separation with near infrared spectroscopy (NIRS)

NIRS analysis was performed with a FOSS NIR SYSTEM 6500 in order to investigate if NIRS can be used to separate sapwood and heartwood. Observations were made in dry state on test objects from three different sites (Paper VII). The instrument measures wavelengths from 400–2500 nm with a step of 2 nm, resulting in 1050 measuring points or X-variables. Every point measures the absorbance in reflectance mode. Each specimen was mounted in a holder. Then the ray was moved over a measurement area 30 mm wide and 8 mm high (Figure 7).

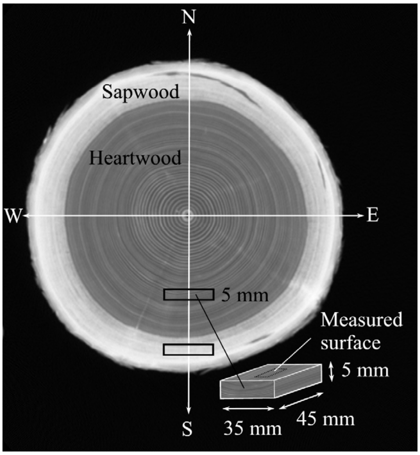


Figure 7. Cross-sectional computer tomography (CT) image of stem discs 5.25 m from butt cut showing specimens for NIR analysis in heartwood and sapwood. In CT images, the intensity in greyscale is proportional to density. Therefore, heartwood appears as dark grey and sapwood as white.

2.6 Volume yield

To evaluate measures to minimize loss of volume yield during production of three given products from Norway spruce heartwood, software simulation of a sawmill breakdown process was used (Paper VIII). Saw simulation techniques used to study the impact on volume yield of log properties or different sawing strategies were based on the Stem Bank and the Saw2003 simulation software (Nordmark 2005). Saw2003 is a PC-based C++ application developed to utilize the digitized data contained in the Spruce Stem Bank and is used to simulate the breakdown process using cant sawing according to the common rules used in Swedish sawmills.

Knot definitions were deactivated in the simulation software, and equal price was set for all products in order to achieve an explicit volume-yield optimization without knot- or price-related influences.

The Stem bank

The Stem Bank is a database based on CT-scanned logs of Scots pine and Norway spruce from different sites in France, Finland and Sweden. The images resulting from CT-scanning of a log are detailed descriptions of outer shape, heartwood border, location of the pith and a nine- parameter description of the knots. The trees were graded according to the Swedish grading system and sawn with normal sawing pattern (cant sawing), and the centre boards were scanned on four sides. All information about the logs, such as the silvicultural and stand data, CT images, sample plot and images of centre boards, was stored in the database (Oja 1999). The detailed data stored make it possible to recreate the outer shape and inner structure of every log using saw simulation software. The information from the stem bank has been used for research and development of software and algorithms for simulations of, for instance, knot structure, optimization of crosscutting and sawing simulations, validation of sawing simulations and separation of heartwood and sapwood of spruce.

2.7 Statistics

All statistical calculations were based on 95% confidence interval and assumption of normal distribution of observations. In Papers I, II and VI, classical statistics was used with software JMP 5.0 (SAS Institute Inc. 2002). In order to compare the mean crack lengths (Paper VI) using statistical methods, data were transformed before analysis by log(1+data), since crack length is not normally distributed. Analysis of variance (Welch approximation) and mean comparison with Tukey-Kramer HSD were then applied. In the statistical test, the p-values were very small, which means that the differences can still be considered significant, although the assumption of normal distribution was approximately fulfilled.

Multivariate statistics was applied in the investigations in Papers III, IV and VII. In order to use all the information in MC gradients in the absorption and desorption process, the MC gradients were analysed with multivariate methods (PLS regression, Eriksson *et al.* 2001) using software from Umetrics, SIMCA P+10 (Umetrics AB 2003) (Papers III and IV). The MC gradient was expressed as 95 variables, each variable represent a MC at a specific position, was centred but not scaled. These 95 measurements were used as predictors (X variables) in the multivariate analysis and as response values (Y-value) for example, heartwood, sapwood or site was used. A high value for the response variable represents a high probability of the observations belonging to the corresponding class. PLS discriminant analysis was used to find a model that separates classes of observations on the basis of their X-variables (Eriksson *et al.* 2001) (Papers III and IV).

To evaluate NIR data spectra, multivariate methods using software from Umetrics, SIMCA P+11 (Umetrics AB 2005), were used (Paper VII). Before PLS analysis, the NIR spectra were preprocessed with OSC (Orthogonal Signal Correction) (Eriksson *et al.* 2001). As responses (Y-variables), two dummy variables were used, heartwood (1) and sapwood (0), which formed two classes (Paper VII).

3 Results and discussion

3.1 Materials

In this study, trees were selected to produce large differences in the parameters that can be expected to control water distribution in the living tree, such as the size of the crown, density, age and access to water. The trees were selected with a breast-height diameter representative for the site. The diameters for the suppressed trees and dominant trees are rather similar within the group, but with a rather large variation in age and density. Table 1 show the characteristics for the test groups.

Table 1. Data for the test trees. Average values of five trees in each group and standard deviation in parentheses. Characteristics: age of trees (Age), annual ring width (R_{width}), density at moisture content (MC) 12% ($D_{12\%}$), diameter at breast height with bark (dbh), diameter at 6 m height with bark (d6h), height of the tree (H), crown height (C_{height}), crown width (C_{width}) and clear bole height (height to first live branch) (C_{limits}), heartwood content (H_{cont}) i.e., area of heartwood/total cross-section of the stem without bark 0.25 m from butt cut.

Site	Age (years)	R_{width} (mm)	$D_{12\%}$ (kg/m^3	dbh (cm)	d6h (cm)	H (m)	C_{height} (m)	C_{width} (m)	C_{limits} (m)	H_{cont}
Wet dominant	66 (2)	2.6 (0.2)	395 (30)	30.7 (0.8)	25.7 (0.8)	21.8 (2.1)	18.7 (2.7)	5.4 (0.7)	3.2 (2.1)	0.46 (0.06)
Dry dominant	158 (10)	1.0 (0.2)	452 (39)	28.9 (1.2)	24.2 (2.4)	22.2 (1.2)	18.9 (1.4)	4.4 (0.5)	3.3 (1.2)	0.58 (0.08)
Wet suppressed	67 (8)	1.5 (0.3)	414 (38)	19.1 (1.3)	15.6 (0.8)	18.3 (1.4)	13.7 (4.1)[1]	3.7 (0.6)	4.7 (5.0)	0.43 (0.10)
Dry suppressed	137 (25)	0.6 (0.2)	491 (28)	17.9 (1.0)	13.5 (1.2)	14.3 (1.2)	10.3 (1.9)	3.5 (0.7)	4.0 (1.0)	0.55 (0.08)
Irrigated (I)	37 (0)	2.0 (0.2)	361 (21)	15.8 (1.3)	9.1 (1.3)	9.8 (0.6)	8.7 (0.8)	3.3 (0.3)	1.1 (0.5)	0.39 [2] (0.05)
Control (C)	36 (0)	1.7 (0.1)	410 (14)	12.9 (1.0)	6.7 (0.5)	8.9 (0.3)	7.8 (0.4)	2.5 (0.3)	1.2 (0.3)	0.12 (0.19)

[1] The crown of one tree was extremely high.

[2] In those young trees, the border between heartwood and sapwood is less distinct, and therefore, some intermediate wood was included in the heartwood area, which gives overestimated heartwood content.

3.2 Field test—above ground exposure

Cracks, upper surface

After 6 months of exposure, cracks were visible on upper surfaces of untreated specimens. After one year's exposure, cracks were also visible on painted sapwood, and after another year, cracks were visible on painted heartwood (Paper VI). Painted heartwood had the fewest cracks and untreated sapwood the most. After about 2–2.5 years' exposure, cracks started to coincide, especially in the untreated sapwood, and some of the end-grain cracks penetrated through both surfaces.

Crack lengths, upper surface

After two years of exposure, the cracks in sapwood were about 3 to 4 times longer on average than those in heartwood for both painted and unpainted specimens (Paper VI). Mean total crack length for sapwood and heartwood, untreated and painted, is shown in Figure 8. There was a significant difference in average crack length between sapwood and heartwood for painted specimens 2004–2007 and unpainted test objects 2003–2007.

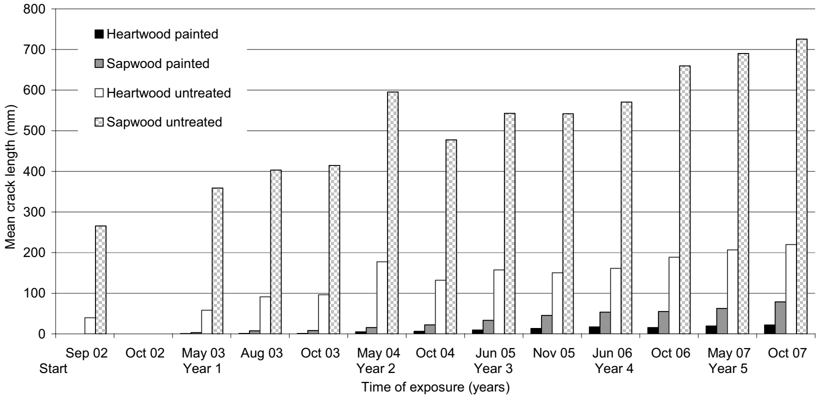


Figure 8. Mean crack length on the 50- x 300-mm upper surfaces of 78 spruce specimens from 2002 to 2007. No measurable cracks were found on one measurement occasion, October 2002.

Site and tree growth

Further analysis based on site and tree growth (test groups in Table 1: wet suppressed, dry suppressed, wet dominant and dry dominant) shows a difference in mean crack length for untreated upper surfaces (Figure 9). The results from this study with a rather limited number of specimens show that the untreated sapwood specimens from the dry site tend to crack most and the ones from the wet site least.

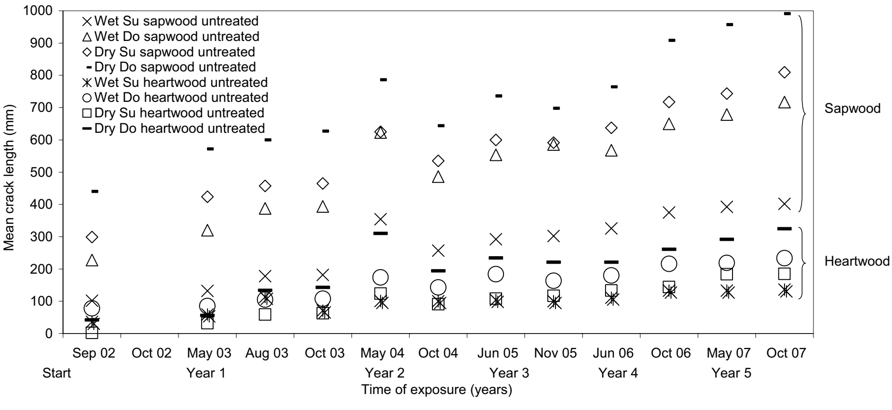


Figure 9. Mean crack length on 50- x 300-mm untreated upper surfaces of spruce specimens from 2002 to 2007.

For untreated heartwood, there was no significant difference in mean crack length on the upper surfaces of the test groups from 2003–2007.

There was a significant difference between the test groups in mean crack length on upper surfaces of untreated sapwood from 2003–2007. Mean comparison with Tukey-Kramer HSD showed that the untreated wet suppressed group differed from the other groups and differed significantly from the dry dominant group from 2003–2007.

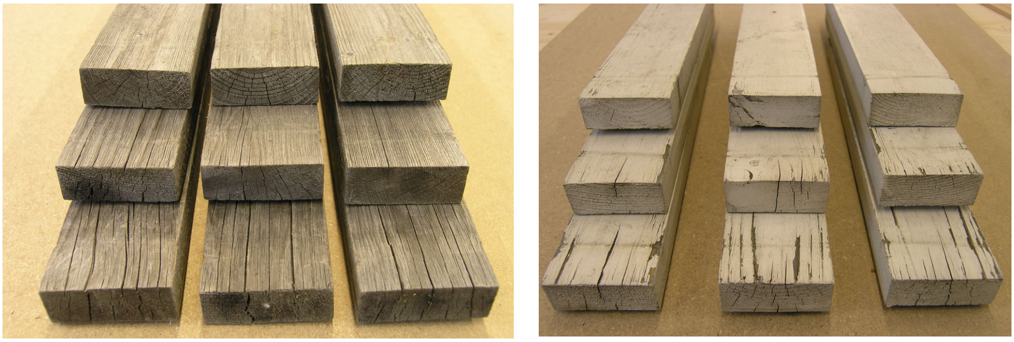
These results may be explainable by a high share of latewood in the periphery of the sapwood together with moisture-related movement of the untreated sapwood surface. Latewood shrinks and swells more than earlywood, and in the tangential direction, high stresses arise in and between latewood and earlywood layers, making this a weak region in the wood structure (Sandberg & Söderström 2006). Sandberg (1999) found on the micro level that the cracks on the tangential surfaces occur frequently in earlywood and latewood of spruce, and delamination in the middle lamellae is especially noticeable in the latewood after weathering. In old trees, narrow annual rings form in the periphery of the trunk; *i.e.*, the sapwood can have a high proportion of latewood (Kollman 1982).

For painted heartwood and sapwood, there was no significant difference in mean crack length between the sites. The untreated surfaces underwent to more moisture-related fluctuation than the painted surfaces, since rain wets the untreated surface faster. The untreated surface dries more quickly in the sun, and that causes high stresses and thus increased cracking. The difference between heartwood and sapwood is probably that heartwood absorbs less water and undergoes slower moisture-related fluctuation.

The main difference in crack formation is due to the presence of either heartwood or sapwood, and the nature of the sites has less influence. Differences in chemical composition between heartwood as sapwood might contribute to the difference. Measurements with NIRS in Paper V indicate these differences. This investigation has a limitation, however, in that it does not investigate what kinds of extractives, chemical compounds and quantities are involved. Other investigations show that there are differences in spruce, but these are rather small. The amounts of extractives vary between 0.5% and 4.2% of dry weight in spruce (Lindgren & Norin 1969; Pensar 1967; Assarsson & Åkerlund 1966). The fatty acid concentration was higher in sapwood (1–4%) and about 1% in heartwood and decreases towards the pith (Pensar 1967; Ekman 1980). Ekman also found that the radial distribution of resin acids and diterpene alcohol showed a similar but weaker trend, and the difference between heartwood and sapwood was smaller. The amounts of sterols and triterpene alcohols in different wood zones of the stem were almost independent of radial location. There were small variations in the amount of extractives distributed vertically in the stem. Bertaud & Holmbom (2004) found that spruce heartwood contained significantly more lignin and less cellulose than sapwood and found significant differences in sugar units in hemicelluloses between latewood and earlywood. The lipophilic extractives were also less concentrated in the latewood.

Visible changes, painted and untreated upper surface

After 2.5 years, some knots started to be visible through the paint, and on some of the specimens, latewood grain rose above earlywood. Through the years, the width and depth of the cracks increased, and some of the end-grain cracks penetrated through both surfaces. After 3.5 years, it was possible to divide the objects into 3 groups according to the criteria in Table 2 (3rd and 4th columns) in Paper VI. Figure 10 shows examples from the three groups after 5.5 years' exposure for a) untreated and b) painted upper surface.



a) b)

Figure 10. Upper surfaces of samples from untreated a) and painted b) spruce. Characteristics of group 1 on the top (best), group 2 in the middle and group 3 at the bottom according to Table 2, Paper VI. Photo: October 2007, after 5.5 years' exposure.

In group 1, heartwood test specimens were predominant. In group 3, sapwood specimens were predominant. In group 2, heartwood and sapwood were mixed. This applies to both untreated and painted surfaces.

Untreated surface

The grey surface was superficial. Microscopic analysis showed that the fibres on the untreated upper surfaces were damaged by weathering, and *Aureobasidium pullulans* was found. Green algae increased on the untreated upper surfaces after a rainy and warm summer season in 2007.

Of the five untreated test pieces examined in 2007, *basidiomycete* hyphae were found on one upper surface, soft rot on three upper surfaces, and only *A. pullulans* on one surface, and no rot. On the end grain of these five test pieces, *basidiomycete* hyphae were found on two, brown rot on three, soft rot on one and only *A. pullulans,* and no rot, on one.

The specimens with many cracks in or close to the end grain became brittle and fragile (group 3 in Figure 10a). These are sapwood specimens mostly from the dry dominant group (compare with Figure 9). Wood of quality similar to these specimens cannot be recommended for outdoor use without painting. Fastenings such as nail and screw are joints very often made close to ends of wood boards. Besides the risk of diminished joint strength over time, there are aesthetic and practical considerations that are likely to entail replacement of the board.

Painted surface

After 5 years, paint was loose along bands of raised latewood, which can be seen in group 3 in Figure 10b. The reason for this may be that there is a large difference in density between earlywood and latewood. On wetting, with raising of grain as a consequence, the paint is subjected to tension at the transition between earlywood and latewood which ultimately causes it to crack and loosen.

Another factor contributing to the loosening of the paint may be that the paint doesn't adhere sufficiently well to the earlywood. Tests have shown that acrylic paint doesn't penetrate into the earlywood of spruce, but rather lies on the surface (de Meijer *et al.* 1998; Miniutti 1963).

In order to speed up the results in this investigation, the best possible surface treatments were not chosen, and no primer was used.

The specimens in the present investigation whose colour coats are still relatively intact after 5.5 years and lack cracks in the end grain come from heartwood.

Discoloration of lower surfaces, painted and untreated upper surfaces

After 1.5 years' exposure, it was possible to visually divide the specimens into 3 groups according to discoloration criteria in Table 2 (1st and 2nd columns) of Paper VI. Figure 11 shows examples of discoloration on the lower surfaces from groups 1 and 3, with untreated and painted top surfaces.

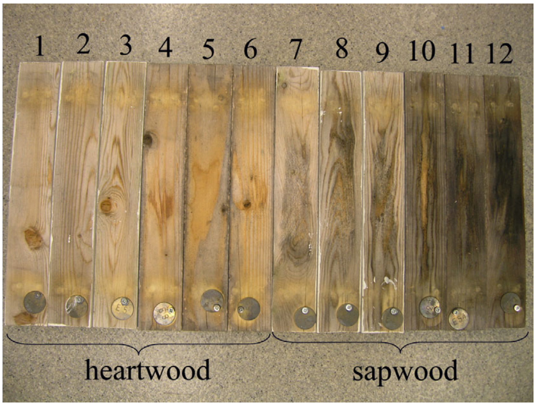


Figure 11. The lower surfaces of spruce specimens with untreated and painted top surfaces. Test specimens from the left: nos. 1–3, three best specimens with painted upper surface in group 1, Table 2, slightly affected; nos. 4–6, the three best from the untreated group 1; nos. 7–9, the three painted specimens with most discoloration from group 3; and nos. 10–12, the three untreated pieces with the most discoloration. Photo taken after 2.5 years' exposure.

There were more heartwood specimens in group 1 and more sapwood specimens in group 3 for both untreated and painted specimens. The coverage and density of discoloration growth did not change markedly after the first evaluation after 1.5 years. However, all surfaces became greyer due to moisture, contamination and dirt, and therefore the scale of greying between the groups became less obvious with time. After about 3 years' exposure, the almost black discoloration faded after a dry and hot summer.

The grey surface was superficial. The wood that was revealed below the grey surfaces of the test pieces looked yellow and sound, except for one specimen that had blue-sap stain going into the wood. Microscopic analysis showed that discoloration on the lower surface was mostly due to *Aureobasidium pullulans* together with a few other discolouring fungi, green algae, white algae and dirt.

Other studies have shown differences in discoloration due to the presence of heartwood or sapwood on Norway spruce. Bergström *et al.* (2005) found differences in discoloration between spruce heartwood and sapwood tested with a Mycologg (Blom & Bergström 2005). Frühwald *et al.* (2007) found more fungal growth, registered by digital photography and evaluated by image analysis, on spruce sapwood than on heartwood. Yang *et al.* (2006) found less mould growth on White spruce (*Picea glauca* (Moench) Voss), Black spruce (*Picea mariana* (Mill.) B.S.P) and White cedar (*Thuja occidentalis* (L.)) heartwood than sapwood after 8 weeks in a mould growth incubator.

Obviously, heartwood of spruce as a less favourable substrate for fungi can explain some of the problems with discoloration on boards, for example, on building facades that are striped with blue sap fungi on one side but not on the other. One reason why heartwood becomes less discoloured can be that blue sap fungi require free water in the parenchyma cells of wood in order to start growing. Continued growth then requires moisture content between 30% and 120%. The amount of time during which this condition can prevail is more limited in heartwood than in sapwood.

Another reason might be lower amounts of nutrients and sugar that serve as food for fungi on the heartwood surfaces. For pine sapwood, the increased growth of discoloration fungi on sapwood has to some extent been explained by higher drying rates and transport of nutrients and sugar that serve as food for fungi to the surfaces, which makes the wood there more susceptible to microbial attack (Theander *et al.* 1993; Terziev *et al.* 1993; Terziev & Nilsson 1999). In spruce heartwood, the transport of nutrients to the surfaces during drying is probably not possible to the same extent due to low water content in green wood, 34%–40% in heartwood compared to 113%–153% in sapwood. Besides that, the highest concentration of sugars is found in the sapwood near the bark and diminishes toward the centre of the tree. The distribution of protein in the cross-section of the trunk is similar to that of sugar (Fengel & Wegner 1989).

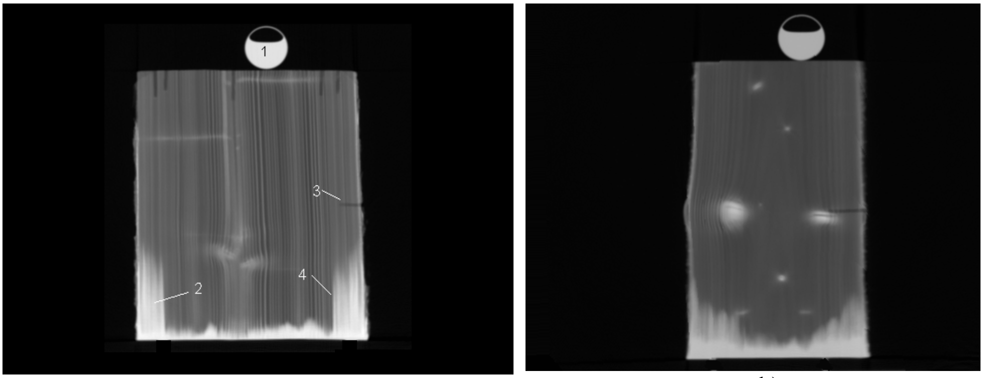
It is possible that even small differences in chemical composition may effect the overall resistance of wood to cracking and decay. It has been found that lignin type, content and pattern of desposit play critical roles at the inception of soft-rot attacks and that relatively minor changes in lignin content can be associated with a large decrease in decay resistance (Zabel & Morrell 1992).

3.3 Measurements of water absorption and desorption in end grain of spruce with CT scanning

Visual evaluation of CT images during absorption

Specimens were CT-scanned after liquid water absorption in end grain for 1, 3, 7 and 14–15 days (Papers I–V). The result was images in which variations in water absorption appear as different intensities in the greyscale, where white areas indicate high density due to absorption of water. Visual qualitative evolution of the images (Paper I) shows that the water absorption pattern varied within the radius of the stem as well as within the height from the absorption surface. Water is not evenly distributed over the rising gradient. Density is greater close to the end grain and decreases higher up in the wood.

The images show that the greatest difference in water absorption and desorption was between heartwood and sapwood. In most cases, the border between heartwood and sapwood was sharp, as in figure 12a. In the young spruce group (Paper IV), there was a diffuse border between sapwood and heartwood compared to the older trees used in Papers I–III. The visual difference in capillary water height between heartwood and sapwood was less obvious than for the older trees in Papers I–III. The images also show knots, and in the middle, the pith can be seen as white areas.



a) b)

Figure 12 Vertical cross-section CT images showing absorption after 14 days in water. a) 65 year old spruce grown wet suppressed. On top of the specimen is a jar with water as reference (1). The intensity is proportional to the amount of water. White areas indicate increased water content (2). A dark streak on the right side of the images shows a reference point 100 mm from the bottom on the north side of the stem (3). Between heartwood and sapwood there is a clear boundary of water absorption (4) b) A 36 year old spruce from the control group.

Top end or butt end immersed in water

One of the objectives of this work was to investigate whether fibre direction makes any difference in absorption depending on whether the test pieces were oriented butt end down or butt end up (Paper I). According to traditional wisdom, panels should be fitted with the butt end up and pith side out. Due to the fibre angle, water should more easily flow down the fibres of the panel (Anon. 1996).

In this investigation, there was no significant difference in $CWH_{40\%}$ between test objects absorbing water with butt end down and those with butt end up. Figure 13 shows samples after 14 days of absorption, a) with butt end down and b) with top end down during absorption and shows the similarities in the absorption patterns between specimens. In Figure 13a, no. 1 shows a jar with water on the specimen that is there for density calibration. One can see a large area (2) with increased moisture content less than 40% in heartwood. Almost the same pattern can be seen in the specimen in b) that has been standing top side up. These two were the only test objects that behaved this way. Figure13c and d show a vertical white streak (3) in the wood and increased water around the pith (4). The white streak was dense compression wood in one annual ring along that stem and did not extend east and west in the stem.

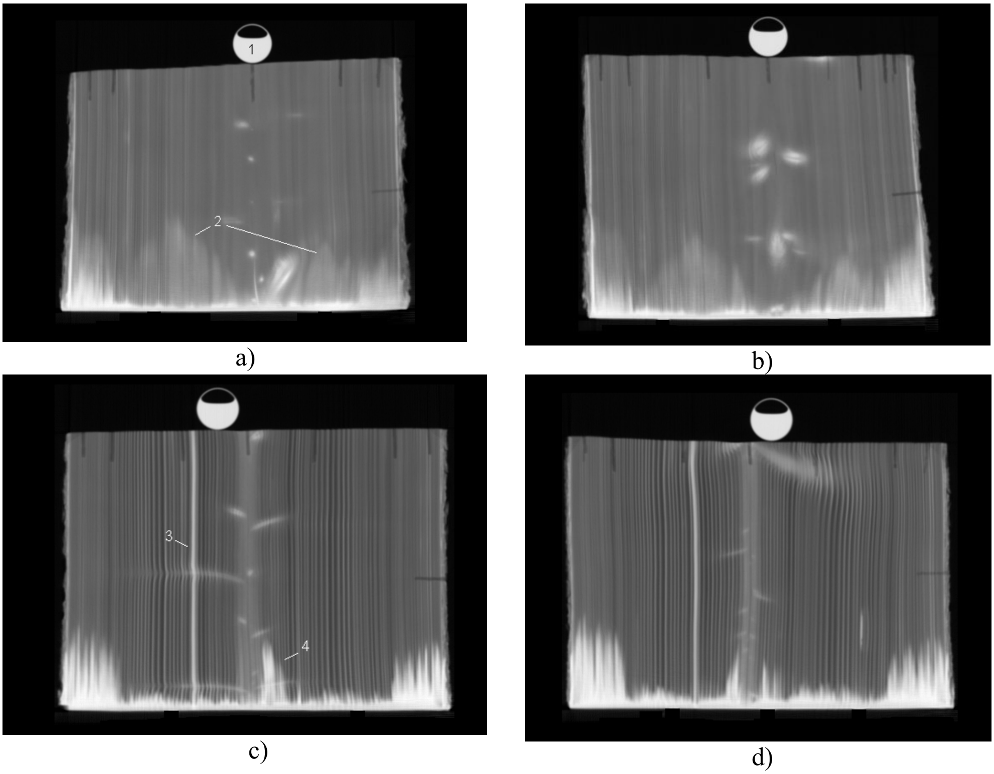
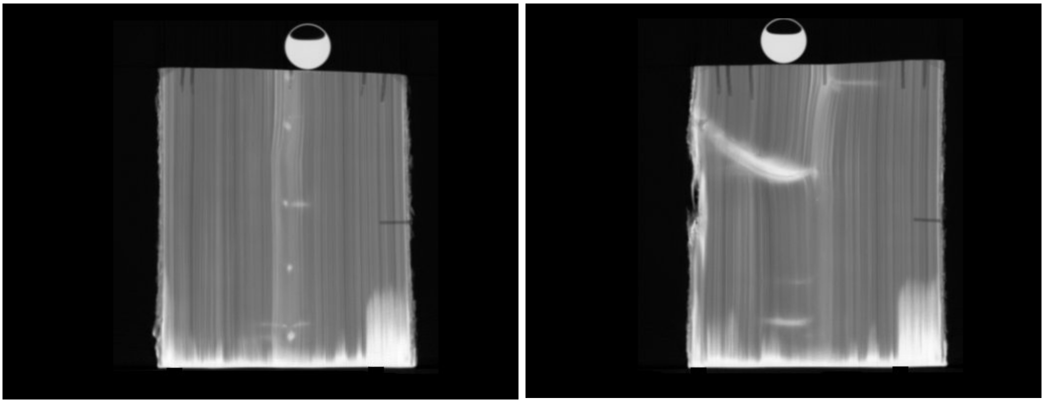


Figure 13. CT images showing capillary water height behavioural patterns after 14 days in water. 1 shows a reference jar containing water. Specimens in a) and c) stand with the butt end in water and in b) and d) with the top end in water. 2 shows increased moisture content (MC still below 40%) in heartwood. 3 shows dense compression wood and 4 shows increased water around the pith caused by root rot. Specimens: a) dominant, without free ground water, butt end down; b) dominant without free ground water, absorption 15 days, butt end up; c) dominant, good supply of water, absorption 14 days, butt end down; d) dominant, good supply of water, absorption 15 days, butt end up.

The capillary water height varies like a wave around the stem. Generally, it differs by a few millimetres between north and south, east and west of the stem. A rather extreme example that deviates from that is shown in Figure 14. The difference is due to a scar on the south side of the stem, to the left in the figure. Apparently, the water transport was changed in the "wound wood", which implies that a chemical transformation of the wood has occurred.



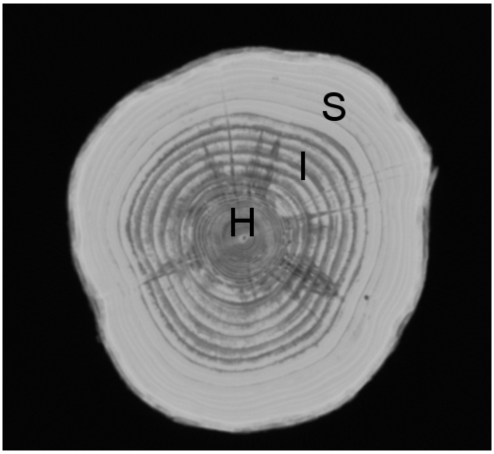
a) b)

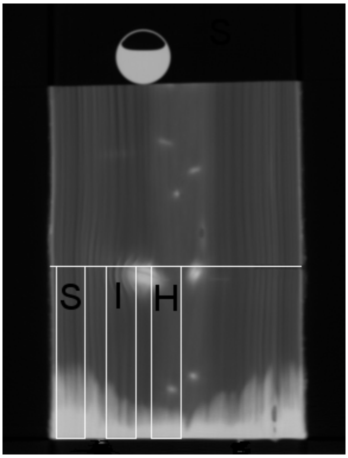
Figure 14 a) and b) show difference in capillary water height patterns between south and north side of the stem caused by a scar. The objects are suppressed, grown without free ground water (dry): (a) butt end down, absorption 14 days; (b) butt end up, absorption 15 days.

To quantify water absorption and desorption, image analysis was used to evaluate capillary water height (CWH) (in fact, volume) and moisture content gradients (MC).

Water absorption in the radius of the stem

It was found that the biggest difference in water absorption was between heartwood and sapwood (Papers I–III and Paper V), which was also shown in the preceding images. The absorption pattern in the young spruce in Paper IV presented a diffuse border between sapwood and heartwood and small differences in capillary water height in different radial positions in the stem when compared to the older trees used in Papers I–III. It was found that even though the visible difference in CWH was small (see Figure 15b), MC gradients differ at different radial positions in the stem, sapwood, intermediate wood and heartwood.





a) b)

Figure 15. a) CT image of a fresh stem disc 250 mm from the butt cut. 36-year-old spruce from the control group without irrigation. Heartwood (H), intermediate wood (I) and sapwood (S). b) A vertical cross-section CT image showing absorption after 14 days in water; S, I and H show where the gradients have been measured in sapwood, intermediate wood and heartwood.

MC gradients from intermediate wood were more similar to MC gradients from heartwood than sapwood during absorption and drying. There was an indication that there was a difference between MC gradients in sapwood from the fast-growing irrigated site and the control site after absorption for 14 days (Paper IV). The model indicates that the observations from the irrigated site generally showed a higher MC level than the observations from the control site.

The big difference in capillary water transport between heartwood and sapwood in spruce is to a certain extent dependent on a higher degree of aspiration, *i.e.,* closed bordered pits between the tracheids, in heartwood than in sapwood. This is probably the main cause of a relatively lower absorption, since the ability to transport water is strongly linked to the tracheids and the bordered pits. Different chemical compositions in the wood can affect the capillary absorption and also the closure of the pits.

In softwood, lower water absorption in heartwood may be due to such factors as more pit aspiration (Stamm 1970), deposits of extractives on membranes (Liese & Bauch 1967b; Bailey & Preston 1969; Fengel 1972) or small pore sizes (Petty & Preston 1969; Stamm 1970).

There was some difference in MC gradient behaviour and heartwood formation between the trees from the three sites. Though they all came from the same research park in the northeast of Sweden, they were grown differently with different properties, such as age and density (see Table 1).

In the group of relative young, fast-grown spruces, sapwood may have just started to convert into heartwood. Heartwood in spruce starts to form close to the pith at an age of about 20–30 years. Probably, the heartwood is not fully developed, but consists of some kind of "preheartwood", here called intermediate wood. The differences probably depend on the fact that the wood is in the process of changing from sapwood to heartwood.

From the CT-scanned cross-sections, one can see variations in greyscale in some annual rings outside the darker heartwood (Figure 15a). That suggests that the density (water content) decreases outside the heartwood with a gradual decline. Heartwood formation on spruce has not been investigated to the same extent as for wood species with visible heartwood, such as pine. Therefore, it is difficult to explain the mechanism behind heartwood formation, and the mechanism causing heartwood is not necessarily the same for all tree species. However, from other investigations, there are indications that heartwood formation can be gradual (Bamber 1976).

Capillary water height

Another objective with this work was to investigate how far from the end grain water could be transported and over what amount of time. The absorbed capillary water height (CWH) was higher in sapwood than in heartwood (Table 2). The average CWH (MC ≥ 40%) was about 3–4 times higher in the sapwood than in the heartwood (Paper I).

Table 2. Average capillary water height (mm) in spruce when MC ≥ 40%, mean values and standard deviation in brackets. 38 observations.

Time (days)	1 day	3 days	7 days	14/15 days
Sapwood	13.9 (3.4)	21.0 (6.3)	27.8 (6.3)	41.5 (8.4)
Heartwood	3.4 (1.3)	5.6 (1.5)	8.6 (1.7)	13.3 (2.6)

14 days in water is extreme, not a normal condition in outdoor use. In this case, the limit for the capillary water height is at a moisture content of 40%, which is above FSP, a limit for growth of decay fungi, with good measure.

The capillary water height (CWH) used in Paper I shows only a single value for a particular moisture content level. The entire MC gradient has more information about the absorption and desorption process. For this reason, the MC gradients were used in further investigations.

Examples of MC gradients after absorption for 14 days (Paper III) demonstrate differences between three specimens (Figure 16). The moisture content close to the surface (MC_{surf}) (average of 5 pixels) was quite similar for all three specimens. Heartwood gradient A shows a steeper and lower gradient compared to samples B and C from sapwood. The gradients show a large difference in capillary water height at a moisture content of 20% ($CWH_{20\%}$). For sample A, the $CWH_{20\%}$ was about 25 mm, compared to 45 and 78 mm for B and C.

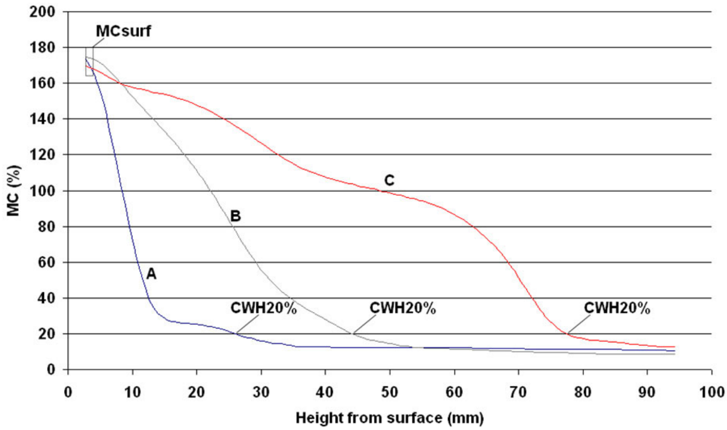


Figure 16. Examples of three moisture content gradients (A, B, C) after water absorption in end grain for 14 days. A shows MC gradients from measurements in heartwood, B and C in sapwood.

Absorption rate

In Paper V, the change in MC over time is shown as an average of moisture content in the respective test groups (Table 1). In Figure 17, the average of the five wet suppressed MCs is shown for 1, 3, 7 and 14 days. There is a considerable difference in gradients from sapwood and heartwood during absorption. The gradients from heartwood are steeper.

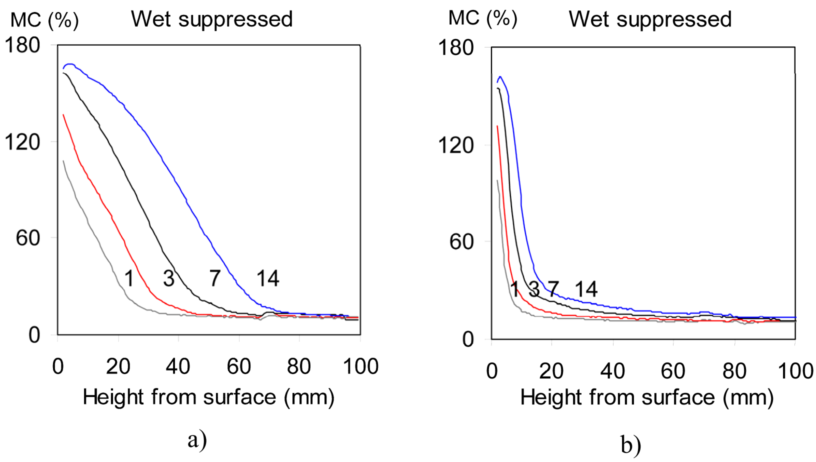


Figure 17 Average of five MC gradients from the test group Wet suppressed measured in sapwood after capillary absorption for 1, 3, 7 and 14 days. Measurements were made 0.8 m from butt cut. a) sapwood b)heartwood.

The moisture content gradient can be compared to the fibre-level simulation described in as in Paper V. The curves in Figure 18 are an average of several simulations. The horizontal axis shows the total length as number of 3 mm long (partly overlapping) fibres. The vertical axis shows the degree of saturation of the fibres; 0 indicates no presence of water and 1 indicates maximum degree of saturation.

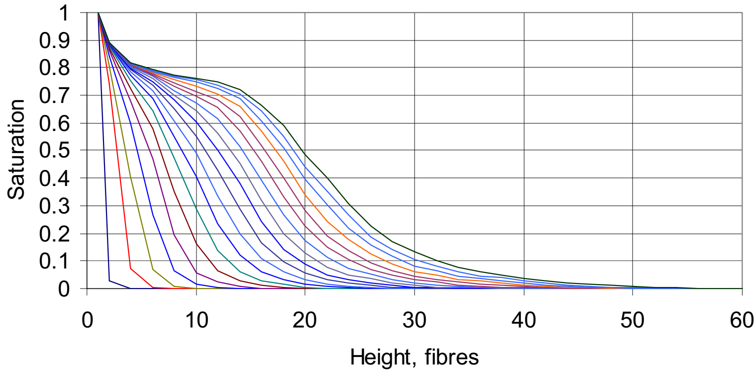


Figure 18. Simulation with percolation method. Each curve is the average of several simulations on a 30 x 30 x 60 network (Radial x Tangential x Longitudinal). The curves are equidistant in the sense that equally many fibres are filled between adjacent curves. "Height, fibres" refers to a virtual height composed of approximately 3-mm-long, slightly overlapping vertical fibres.

Figure 18 illustrates a calculation for aspiration at p = 97.5%, and almost all fibres are eventually filled with water. The lowest horizontal fibre layer is totally filled with water as assumed, but further up the saturation drops, as some fibres are not reached by any flow paths. Rather rapidly, an equilibrium saturation is reached, *i.e.*, new paths are found with the same rate as old ones are blocked. This equilibrium is seen as a horizontal plateau at about 75 %–80 % saturation. This level in the graph is thus an indirect measure of the openness of the fibre structure. There are similarities between the measurements and simulated gradients, but it is clear that the simulation model has to be improved in order to reach a complete agreement.

The average MC gradients in Figure 17 show an even increase in absorption from day 1 to 14 days. To display the water uptake over time, the MC gradients were converted into absorption rate, the surface area under respective MC gradient was calculated corresponding to absorbed volume of water and plotted as a function of the square root of time. This gives approximately straight lines from the regression lines Figure 19 and Figure 20.

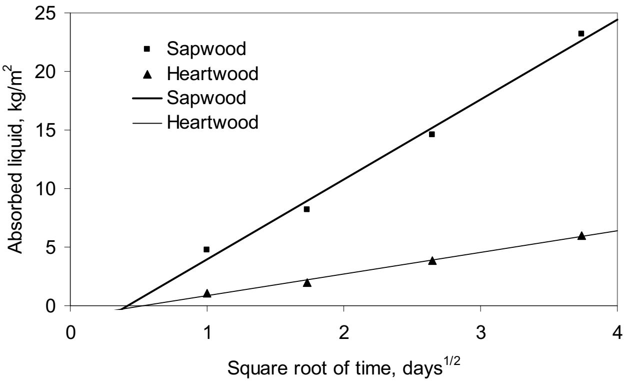


Figure 19 Absorption rate for spruce test group wet suppressed. Absorption is expressed per area of wood with about 12% MC

Figure 19 presents typical absorption rate results for sapwood and heartwood. A clear difference between sapwood and heartwood can be seen. The experimental points are located close to straight lines with square root of time as an independent variable. The regression lines do not go through the zero point, giving an impression of a time lag.

In Figure 20, the corresponding regression lines are forced to go through the zero point in order to make it easier to compare the different test groups. It is interesting to note that for both sapwood (with one exception) and heartwood, the slope of the lines in Figure 20 increases with increasing density. In addition to this density dependency (R^2 = 0.82 for sapwood and 0.96 for heartwood), there seems to be no other difference between the test groups. This indicates that the growth site has no directly significant influence—only the wood density does, which of course in turn may be growth-site dependent.

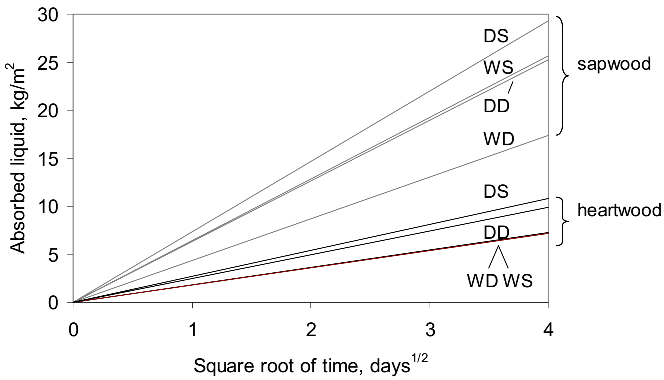


Figure 20 Absorption rate for different spruce test groups. Absorption is expressed per area of wood with about 12% MC. Test groups in Table 1, DS (dry suppressed), DD (dry dominant), WS (wet suppressed), WD (wet dominant).

CT-scanning during three cycles of liquid water absorption and drying
In Paper II, MC gradients were measured during absorption for 1, 3, 7 and 14–15 days and during drying in room climate. The cycle was repeated 3 times. During absorption in sapwood, the moisture-content gradients decreased from cycle 1 to cycles 2 and 3, which was a prominent feature after 14 and 15 days of absorption. The water front receded towards the surface of the test object with increasing test cycles (see Figure 21a). The MC gradients in heartwood follow almost the same steep gradient during all three cycles shown in Figure 21b.

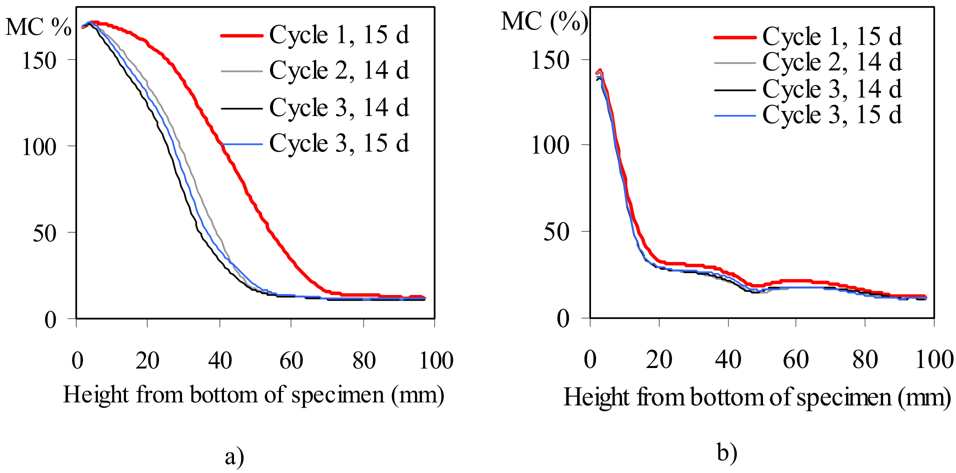


Figure 21. MC gradients from absorption for 14 and 15 days repeated 3 times; a) sapwood, b) heartwood.

The repeated cycles of absorption and desorption in Paper II show that MC gradients measured in sapwood approached each other in cycles 2 and 3. The differences are probably due to the occurrence of pit aspiration when the wood is resoaked, to air blockage from air in the water or to contaminants and extractives that block the pits. MC gradients in heartwood generally follow almost the same gradient during all three cycles. The differences between sapwood and heartwood probably depend on heartwood having more aspirated pits from the beginning. This was done to gain insight into how wood reacts to repeated soaking and drying. This may indicate how wood will respond to the moisture dynamics of long-term outdoor exposure.

Variation in MC gradients within the stem
Paper III describes the variation in MC gradients within the stem after absorption in end grain. 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 as far as the height of the trees is concerned (0.8, 5.8 and 9.5 m from butt cut). In heartwood, there was a difference in MC gradients measured 0.8 m from butt cut compared to gradients measured 5.8 and 9.5 m from butt cut during absorption for 14 days and desorption for 3 days. The difference between specimens in heartwood probably depends on differences in heartwood properties 0.8 m from butt cut, such as reaction wood, fibre variation and root rot close to the root.

The differences in liquid water absorption dependent on the vertical position within the tree were, in other words, generally small. The study of the specimens in Paper I shows similar results during absorption with top end or butt end down. 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.

Variation in MC gradients due to growing condition

The behaviour of the MC gradient pattern depends on the growing site. Trees grown on a dry site behave differently from the trees grown on the wet site in both heartwood and sapwood during absorption and desorption (Papers I and III). PLS-DA analysis shows that after absorption for 1, 3, 7 and 14 days, 81%, 79%, 94% and 92% of the MC gradients were correctly predicted into wet (F) and dry (T) for sapwood and 96%, 77%, 78% and 76% for heartwood (Paper III). The difference in moisture content gradients between the wet and the dry sites seems to be greater in sapwood than in heartwood.

Generally, MC gradients from the dry site have a lower MC_{surf} than those from the wet site, but a higher CWH. The wet site has a higher MC_{surf}, but a steeper gradient. Whether or not the trees have grown as dominant or as suppressed has no influence on moisture-content gradient during absorption and desorption (Paper III). Differences were also found when absorption rate was calculated (Paper V) and when capillary water height was calculated (Paper I).

The 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 within the groups and comparably the same between the groups, but there were major differences in density, age, annual ring width and size of the crown 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. On the dry site, the moisture-content gradients of heartwood were easier to predict. 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. That can be the cause of the different heights and shapes of the gradients.

Good access to water and nutrients results in large lumina, and less access to water results in more latewood with thicker cells and higher density. During periods of high availability of water, crown elongation, production of auxin and formation of earlywood continue. Low access to water produces latewood in which differentiated cells remain alive longer and the cells become considerably thicker than those in earlywood (De Zeeuw 1965; von Pechman 1958;).

Desorption in room climate

An important property of wood in outdoor use is the ability to dry. If wood dries fast, there is a shorter wetting time and thus a shorter time with optimal conditions for fungi to grow. In these investigations, heartwood generally reaches a dry level before sapwood after absorption and drying in room climate (Papers I–III). Another aspect of the matter is that heartwood initially had a lower MC level.

The test objects from the "wet dominant" and the "wet suppressed" groups showed the lowest CWH in sapwood (Paper I). However, specimens from "wet dominant" dried more slowly. This led to the conclusion that a low CWH does not guarantee the fastest drying. The quantity of water and the wood structure must be considered as well. Paper III indicates that MC gradients from the dry site reach a lower MC faster than test objects from the wet site.

Figure 22 shows examples of MC gradients during drying for 1 and 2 days after three cycles of wetting and drying. During desorption, cycles 2 and 3 reach an MC level below 20% sooner than cycle 1 for both sapwood and heartwood (Paper II.

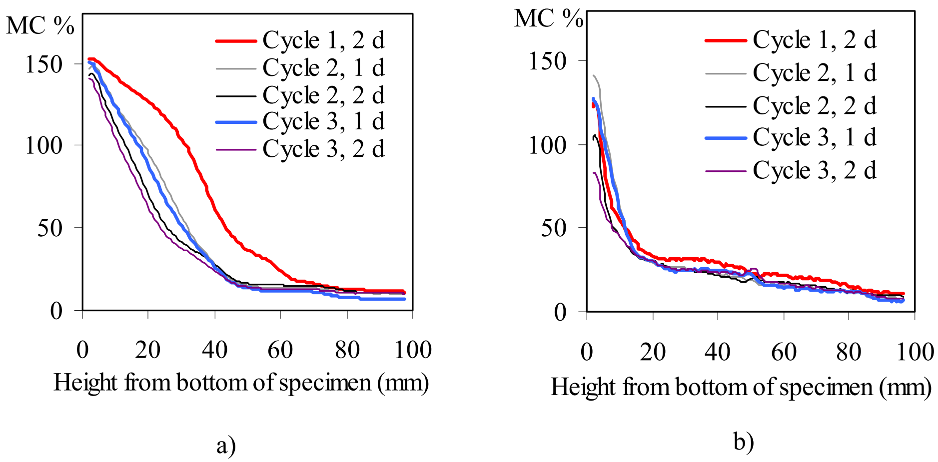


Figure 22. Desorption gradient for 3 cycles. Specimen from "dry suppressed" group: a) sapwood for 1 and 2 days, cycles 1, 2 and 3; b) heartwood for 1 and 2 days, cycles 1, 2 and 3.

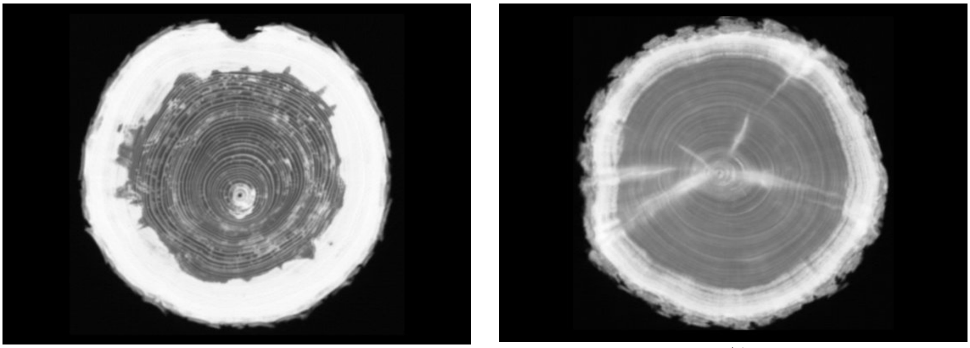
In Paper IV, during drying, differences between heartwood, sapwood and intermediate wood decreased with time. After 2, 3 and 4 days, 74%, 70% and 67% of the MC gradients were predicted correctly into sapwood, heartwood and intermediate wood. MC gradients from intermediate wood were closer to MC gradients from heartwood than sapwood during absorption and drying. The models indicate that the observations from the irrigated site in general had somewhat higher MC level than the observations from the control site after absorption for 14 days and desorption for 2 days.

3.4 Heartwood content

Visually, it is difficult to separate heartwood from sapwood in spruce when the surface has dried. In the fresh state, the border is visible, and heartwood appears whiter than sapwood.

In this investigation, heartwood content was detected in two ways. The heartwood/sapwood border was marked with a highly water-resistant permanent marker on the stem disc in the forest in frozen condition. When spruce is frozen, the border is easy to distinguish, and heartwood appears as white, while sapwood appears as yellow. The discs were stored in a freezer in plastic bags until CT scanning, and heartwood content was calculated with image analysis.

CT images of stem discs in the fresh state were used to determine heartwood content (Papers I, IV and VII). Greyscale distribution in image shows variation in green density of the heartwood (dark grey) and the sapwood (white) (Figure 23). In this investigation, there was a difference in heartwood content between the trees. The trees from the dry site were about twice as old as the trees from the wet site and had significantly larger heartwood content (Table 1) than the trees from the wet site. The suppressed trees from the two sites had approximately the same breast-height (BH) diameter, and a similar relationship obtained between the dominant trees from the two sites (Table 1).



a) b)

Figure 23. CT images of a fresh stem disc 250 mm from the butt cut. Tomography images show the average density of a 10-mm-thick stem cross-section: a) shows a suppressed spruce growing with a good supply of water. $Area_{heartwood}/Area_{tot} = 0.52$, $Diameter_{tot} = 187$ *mm,* $Diameter_{heartwood} = 128$ *mm. Age 65 years. b) shows a suppressed spruce growing on dry site.* $Area_{heartwood}/Area_{tot} = 0.64$, $Diameter_{tot} = 174$ *mm,* $Diameter_{heartwood} = 145$ *mm. Age 145 years. Note that the diameter scale varies between the figures.*

On average, the share of heartwood was 40% in the spruces grown in moist soil (wet) and 57% in the spruces grown in dry soil (dry), including both butt logs and middle logs. There was no significant difference in the share of heartwood between butt log (0.25 m) and middle log (5.25 m). The share of heartwood in the middle logs averaged 46% while the butt logs averaged 51%. The share of heartwood decreases somewhat towards the top, but there was no significant difference. Heartwood was irregular close to the butt cut, but became more concentric towards the top of the tree.

The heartwood content from "The stem bank" shows that there is a large spread in heartwood content (Paper VIII). Figure 24 shows the log top diameter plotted versus heartwood share of top diameter on 750 individual logs. The R^2-value is relatively high, 0.89 thus indicating a high degree of explanation. However this accuracy of prediction is insufficient for use in selecting logs with sufficient heartwood top diameter to ensure 100% heartwood content in the finished products.

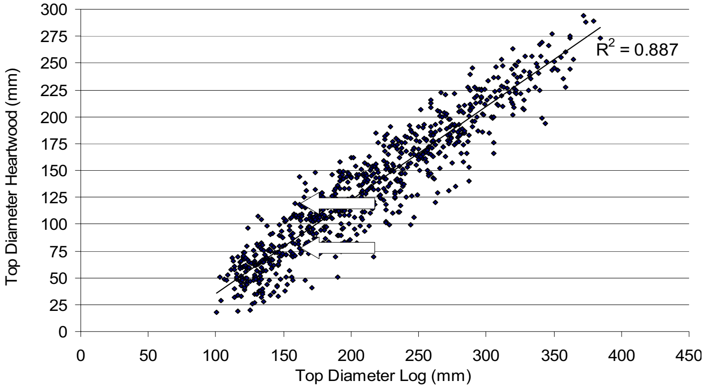


Figure 24. Heartwood top diameter plotted versus log top diameter of 750 logs in the Spruce Stem Bank. Logs with identical top log diameter can show a large spread in heartwood top diameter. Two logs in the Spruce stem bank show the same top diameter, 161.6 mm, but the heartwood diameter is in one case 119 mm and in the other case 77 mm (positions marked by arrows).

It is not only the share of heartwood that counts, the quality matter as well. For the young trees that had been irrigated with water and nutrients and the control group in Paper IV and Paper VII, the greyscale value varies between the images, which show a variation in MC in green stems. Outlining the border between heartwood and sapwood was considerably more difficult on these trees than on the older trees, since there are intermediate zones as well. In the calculation, the darker grey intermediate wood was categorized as heartwood and in Figure 15a, only the dark part in the middle was categorized as heartwood.

The irrigated spruces had larger heartwood content, 39%, than the trees from the control group, 12%, (Table 1). There are differences in heartwood content, even though the trees are within the same age. It seems that faster growth in irrigated trees starts the heartwood formation earlier than the ones from the control group.

3.5 Practical implications of the results

Separation of heartwood and sapwood

Spruce is regarded as and used as a homogeneous material, and spruce heartwood has not been utilized in products for exterior use aboveground in a controlled way. One reason for this may be that is impossible to visually distinguish sapwood from heartwood when dried. As shown above, heartwood variation between individual spruces is large, so relying solely on diameter to increase heartwood content is not practicable. To utilize the better properties of heartwood to produce more durable products with even quality, such as cladding, it is necessary to identify and separate heartwood and sapwood during processing in sawmills. In order to secure nearly 100% heartwood in the products, it is necessary to be able to define the border between heartwood and sapwood consistently.

The most reliable way to separate heartwood and sapwood in green state today is by X-ray LogScanner in log sorting (Oja & Grundberg 2004; Skog & Oja 2009) or with laser technique in green sorting line (Oja *et al.* 2006). Simulations have shown that it is possible to sort spruce heartwood by X-ray scanning (Oja *et al.* 2001).

In order to secure heartwood of good quality, models must be developed to guarantee that high-quality heartwood is being used. The methods used must be precise and be able to deal with the uneven borders between heartwood and sapwood. To ensure heartwood quality suitable for outdoor use, the diameter of the tree and the age and/or the annual-ring width must be taken into consideration so that logs with large heartwood content are chosen. As seen in Figure 9, the untreated heartwood from the wet and dry suppressed spruce had the fewest cracks. The average diameter for those groups 6 meters from butt cut was 15.6 cm respectively 13.5 cm (Table 1). In the saw simulation (Paper VIII), with those assumptions, no logs were approved beneath a top diameter of 21.5 cm. How best to balance economic requirements against making the best use of spruce heartwood is still an open question.

In Paper VII, it was shown that a separation of sapwood and heartwood of spruce in dry state was possible with NIR spectra measured in a laboratory environment and evaluated with multivariate analysis. The visible-wavelength spectrum has a significant influence on the predictive power of separation models. The wavelengths with the most impact on the model were within 2400–2500 nm, 430–450 nm, 2300–2370 nm, 1940–1950 nm, 2110–2150 nm and 1456–1498 nm, listed in order of importance. Wavelengths 430 to 450 nm are within the visible light spectrum. The wavelength interval with the greatest impact on the model was 2400 to 2500 nm, which might be due to differences in organic substances such as cellulose, starch and protein (Shenk *et al.* 2008). That indicates that there are differences in chemical composition that are measurable and might be valuable in assuring heartwood quality. That has to be confirmed with chemical analysis of the wood and more calibration, but perhaps NIR can be further developed for use as a method to ensure the quality of spruce heartwood.

As moisture content and temperature variations affect NIR measurements rather much. NIR measurements can entail problems in an industrial application.

Volume yield

The share of heartwood influences yield and, thus, to some extent determines which products the heartwood can be used in. In Paper VIII, the volume yield was simulated for requirements of 100% heartwood for common dimensions: 44 x 150, 63 x 150 and 63 x 175 mm. Four sawing patterns with various diameters and various numbers of side boards were simulated. In general, the results showed that the number of approved logs increased with increasing top diameter. Since there are fewer logs with optimal diameter, the total volume of possible heartwood timbers will be limited. Volume loss caused by the necessity of increasing log diameters in order to obtain 100% heartwood planks can to a high degree be compensated for with optimized sawing patterns and pricing of products.

In Paper VIII, dimensions that are common products on the market today were studied. It was found that the top-diameter interval for favourable production of product 63 x 175 contained only 6 logs. Since the number of approved logs is limited, the product 63 x 175 might not be suitable for heartwood products at all. If the width 175 mm is necessary for some reason, there may be better solutions, such as gluing together parts with smaller dimensions, that will have the added benefit of increasing dimensional stability.

Service life

How long will the superior durability qualities of heartwood last in comparison with sapwood? In this study, after 1.5 years' outdoor exposure aboveground, more discoloration growth was observed on sapwood than on heartwood, and there were more cracks in the sapwood. This trend was clear from the first evaluation and remained during the whole test period of 5.5 years. After 5.5 years' exposure, initial decay was found on the surfaces and end grain of the untreated specimens. As previously stated, degradation of wood is a complex process involving interaction between wood, the blend of microorganisms, climate and moisture content, exposure time, surrounding environment, irradiation, temperature, *etc*. Decay and weathering can be unevenly distributed on specimens or even invisible to the naked eye. Since the environmental requirements of fungi vary, fungal growth will vary depending on the limitations dictated by the prevalent environmental factors. Decay above ground does not appear to develop in a smooth continuum from year to year. De Grooth & Highley (1995) found in some years, substantial bursts of decay occurred after a period of lag in development, while in other years, decay showed little progress above ground. An overview by Brischke & Rapp (2008) of potential inhibitory effects that might delay the start of fungal activity included competition, antagonism, inhibitory extractives, wood preservatives, insufficient permeability, hydrophobic behaviour, distance from sources of infection, adverse moisture conditions and UV light.

Cracks promote water absorption and provide places where dirt can accumulate, thereby increasing the risk of decay and reduction of strength. Apart from that, growth of discoloration fungi and cracks are an aesthetic liability. To improve performance and to produce uniform, high quality products for outdoor use, such as facades, it is of great importance to better utilize the properties of spruce heartwood to avoid cracks and discoloration. The natural resistance of spruce heartwood is also of importance for building products in general, since free water from dew, rain and condensation can have a deleterious influence on wood that is normally protected from rain, such as under a roof overhang or in a carport.

Blue-stain fungi do not in themselves cause decay or reduction of strength properties. But besides the fact that their visual effect isn't aesthetically pleasing, blue stain fungi increase the permeability of the wood surface, which in turn can increase the risk of attack by rot fungus. It has also been found that blue-stain fungi (*Pullularia pullulans*) in laboratory tests can attack the film-forming finishes, clear lacquers and pigmented paints (Sell 1968). It was shown that the fungus could bore through thick film as well, and that priming coat impregnation below the surface coating did not protect against blue-stain fungi. Blue sap fungi can also grow between the surface and the paint. Bardage (1997) showed that blue-stain fungi and decay fungi were capable of penetrating microspores smaller then 0.6 µm or wider, but none of the fungi were able to penetrate microspores smaller than 0.2 µm. In the investigation, waterborne paint purchased from stores was used on spruce wood of varying dimensions. It was assumed that the adherence of spores of blue-stain fungi not only depended on the paint film, but also on the surface being sufficiently moist for a critical period of time (Bardage 1997). Therefore, heartwood of spruce should be investigated as a poorer substrate for fungi than sapwood.

From a practical point of view, surface treatment cannot ensure freedom from decay. Freedom from the deleterious defects of water can be achieved by careful selection of heartwood products, suitable surface treatment and correct construction methods that prevent wetting and allow drying.

4 Conclusions and future research

Summary

As mentioned in the introduction, many results point out that the presence of large amounts of water in wood is a very important parameter that affects its resistance to degradation. This work has clearly shown that Norway spruce is not a homogenous material. Spruce heartwood absorbs less water and dries faster than spruce sapwood. Hence, consistent use of spruce heartwood in outdoor situations should increase a product's service life compared to products that combine heartwood and sapwood.

Heartwood had fewer and shorter cracks and less surface-discolouring fungus growth than sapwood. This was valid for both painted and untreated wood. Painted heartwood had the shortest crack lengths, and untreated sapwood the longest crack lengths, on both the upper surfaces and the lower surfaces of the specimens. After two years' exposure, the cracks in sapwood (upper surface) were more than 3 times longer and about 5 times more numerous than in heartwood for both painted and untreated boards. Microscopic study shows that surface discoloration is due mainly to *Aureobasidium pullulans* together with a few other discolouring fungi.

The main cause of the difference in the rate of degradation between heartwood and sapwood would seem to be that heartwood of spruce absorbs less water than sapwood and is thus less subject to moisture-related movement in the wood. The investigations in this work show that there was a difference in water absorption between heartwood and sapwood. Sapwood of spruce had 3-4 times higher capillary water height than heartwood. Spruce heartwood absorbs less water than sapwood and thus dries faster. The difference in water absorption between heartwood and sapwood is mainly due to the presence of more aspirated pits in heartwood and a different chemical composition than sapwood.

Conclusions

- These studies have shown that there are differences between heartwood and sapwood of spruce and that there are methods of separating them in both green and dry state.
- All heartwood in spruce has not equal properties. It was found that in the young trees, the indistinct border between heartwood and sapwood in the CT images probably indicates the existence of not-fully-developed heartwood, here called intermediate wood.
- By using a nondestructive method, CT scanning, it was possible to study water distribution in wood during liquid water absorption and desorption. Through image processing, it was possible to measure the differences in water uptake and distribution in wood. A technique was developed for evaluation of the MC gradients with multivariate techniques.
- The studies point out the possibilities of using such techniques as NIRS to separate spruce heartwood saw simulation to explore the viability of production of products of 100% heartwood and simulation with a fibre network to better understand the process of water uptake in wood. Methods for identifying and separating spruce heartwood will need to be refined before they can be employed in industrial production.
- Saw simulation has shown that it is possible to produce boards for outdoor cladding with 100% heartwood. However, the products have to be sawn from bigger logs than are normally used today. This has a negative effect on the yield, but this can be compensated for by extracting more side boards or by higher sales prices.

Future research

Further research needs to be done to validate the results and explain some of the phenomena that have been observed in this work.

- In this thesis, simulations with percolation as a fibre network were used. There are many possibilities for improving the simulations, but for the time being, the computer simulations are extremely time intensive.
- It would be good to follow up the field test that has now been in progress for seven years and observe the long-term degradation of the test objects.
- Industrial techniques for distinguishing heartwood of spruce, such as X-ray log scanners in timber sorting or laser technique in the green sorting line, can be refined, and algorithms to secure a high quality of heartwood can be improved. NIRS could be investigated for its usefulness in ensuring the quality of heartwood and investigating the chemical content of spruce heartwood.

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I

Influences of growth site on different wood properties in spruce sap-/heartwood using CT scanner measurements

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Abstract

This investigation shows how different parameters affect liquid water absorption in Norway spruce, which in its turn affects product life length and need of maintenance.

Logs from 20 trees, half of them suppressed and half of them dominant, were taken from two sites. One site had a good supply of free water (wet) and the other site was without free ground water (dry). The logs were of approximately the same breast–height diameter. The logs were sawn into boards and dried to 12% moisture content (MC). In order to evaluate water absorption, wood density and moisture content were measured by computed tomography (CT) scanning and image processing. The measurements were performed in room climate by CT scanning after 1, 3, 7 and 14–15 days of liquid water absorption in end grain and during desorption for 6 days.

The most important findings in this investigation were:

- Large differences in water absorption were observed between heartwood and sapwood. The absorbed capillary water height (CWH) is higher in sapwood than in heartwood. The average CWH is about 4 times higher in the sapwood than in the heartwood after 24 hours of water absorption (MC $\geq$ 40%). After 14 days of water absorption the average CWH for sapwood was on the order of 3 times higher than for heartwood. There was a significant difference in heartwood/sapwood ratio between specimens from the "wet dominant" group and the other groups. Specimens from the "wet dominant" group showed the smallest difference in CWH between heartwood and sapwood.
- Specimens from the "wet dominant" and the "wet suppressed" group showed the lowest CWH in sapwood. There was a significant difference in CWH in sapwood between specimens from the "wet dominant" group and the "dry suppressed" group and the "dry dominant" group for 7 and 14-15 days absorption.
- Specimens from the "wet suppressed" group and the "dry suppressed" group had the lowest CWH in heartwood. There was a significant difference in CWH in heartwood between trees from the "wet suppressed" group and the other groups for 7 and 14–15 days' absorption
- There was no significant difference found in CWH between wood specimens standing with butt end or top end in water.
- Trees grown with poor access to water had a larger share of heartwood and grew more slowly than trees that grew with a good supply of water.

1 INTRODUCTION

1.1 Background

For decades, the durability of wood material has been secured by preservative treatments. However, environmental considerations have resulted in rules regarding chemical preservation of wood against fungi becoming tougher or even prohibitive. When wood is used in building construction there should be requirements on raw material and construction design for solutions that assure good durability. The durability of wood products depends not only on their resistance to microorganisms but also on wood's tendency to absorb capillary rainwater (Sell 1982). Wood absorbs water 1000 times faster by direct contact than by diffusion in vapour phase (Holbrow et al.1972). Damage to wooden constructions most commonly occurs in the end grain of the products. Microorganisms, mainly fungi and bacteria, have different requirements on their environments in order to live and propagate. Generally, the optimal moisture content for wood-rotting fungi is between 28% and 45%, and the optimal temperature is between 25º and 32°C. Apart from durability, water absorption also affects dimensional change and strength.

Long ago, before forestry became industrialized, wood for construction was selected based on knowledge of the differences in quality and function between the trees. To know if the wood was suitable, parameters such as crown size, bark features, stem properties, site and branches, etc., were considered in judging quality (Anon. 1985). Pine heartwood is considered to be more durable than sapwood because it generally contains more extractives and absorbs less water. Spruce heartwood and sapwood are difficult to separate, and probably for that reason their properties have seldom been investigated. It has been shown that in sound Spruce stems the amount and composition of extractives were dependent on the radial position of the wood sample. Fatty acid concentration was higher in the sapwood and decreased towards the pith (Pensar 1967; Ekman 1980).

In this study trees have been selected to produce large differences in the parameters that can be expected to control water distribution in the tree, such as the size of the crown, density, age and access to water. The use of CT scanning permits mapping of water distribution during end-grain liquid absorption, which can be shown visually by image processing. Traditionally, panels should be fitted with the butt end up. One of the objects of this study was to investigate whether fibre direction makes any difference in absorption between butt end down or butt end up. Another object was to measure how far from the end grain water could be transported to cause damage. A future aim is to model parameters explaining water absorption in Norway spruce (*Picea abies* (L.) Karst). The parameters should be measurable in the industrial chain from tree felling to the sawing operation on line and make it possible to separate appropriate raw material for products that require low water absorption. The hypothesis is that differences in water absorption and desorption in the end grain cause differences in durability for building products, since micro-organisms in wood need a moisture content (MC) over the fibre saturation point (FSP) to cause degradation. In other words, increased product life and decreased maintenance requirements for spruce products used outdoors above ground can be expected from choosing wood in a systematic way related to a number of characteristics that affect water absorption. In the future an X-ray Scanner might be used as a tool to control these parameters in the sawmill process (Grundberg 1999).

2 MATERIALS AND METHODS

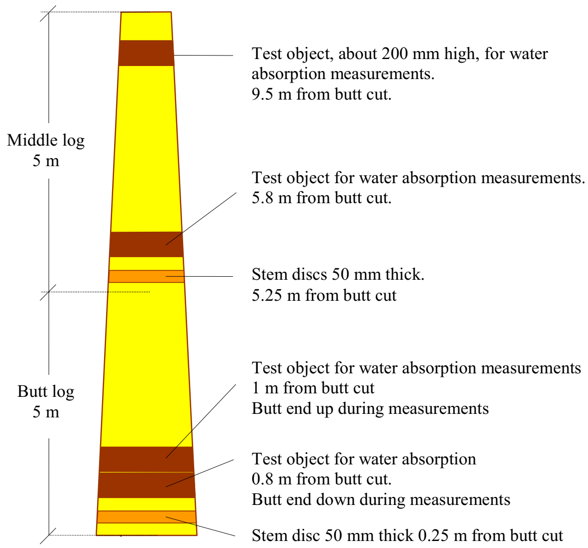
2.1 Materials

Twenty trees of Norway spruce (*Picea abies* (L.) Karst.), half of them suppressed and half of them dominant, were taken from two sites. One site had a good supply of water, and one site was without free ground water. The spruces from the dry site were grown on a typical ”sandy heath” 175 m above sea level with an average age of 148 years. The dominant trees had an average diameter at breast height of 29 cm, and the suppressed trees an average diameter of 18 cm. The spruces grown on “moist forest land” 250 m above sea level had an average age of 67 years. The dominant trees had an average diameter at breast height of 31 cm and the suppressed an average diameter of 19 cm. Different characteristics for the four test groups are shown in Table 1.

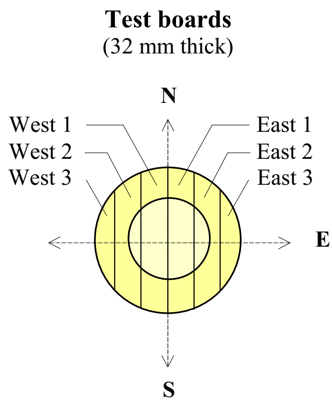
Table 1. Different characteristics for the four test groups.

Test group Average - five trees in each group	Age (years)	Growth rings width (mm)	Density (MC 12%) (kg/m^3)	Breast height diameter (cm)	Height (m)
Wet suppressed	67	1.5	414	19	18.3
Dry suppressed	137	0.6	491	18	14.3
Wet Dominant	66	2.6	395	31	21.8
Dry Dominant	158	1.0	452	29	22.2

Stem discs 5 cm thick were cut 0.25 m and 5.25 m from the butt cut and stored in plastic bags and frozen until CT scanned. The trees were cut into 5-m logs. The logs were sawn through and through in north-south direction to 32 mm thick boards and dried to 12% MC. Test objects for absorption testing 200 mm high were cut from 3 different heights (see Figure 1). In this investigation only test objects from the butt log end were investigated.



a)



b)

Figure 1. Sketches showing a) how the trees were divided and where the test object can be found in a stem, b) sawing pattern.

The test objects were placed in a climate of standard conditioning RH 65% and temperature 22ºC (corresponding approximately to MC 12%) for more than two months. The sawn flitches from the same height of the tree were assembled with a distance of 12 mm into one test object (see Figure 2).

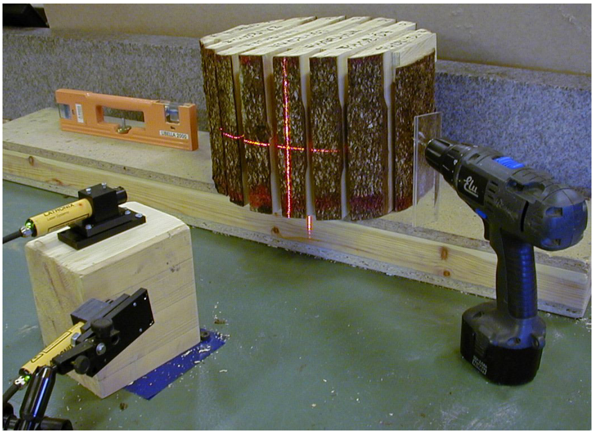


Figure 2. To ensure correct repositioning in the CT scanner, lasers were used to mark vertical reference points. Here a 3-mm-diameter drill was used to make the holes 100 mm from the end grain.

2.2 Absorption and desorption of water

Test objects were placed in a basin on bars of stainless steel in 5-mm-deep tap water for end grain absorption. The measurements were performed in room climate with the aid of a CT scanner after 1, 3, 7 and 14 days standing with butt end in water during absorption. The scan followed the grain in the middle of each board and was 10 mm wide. The test objects standing with the top end in the water were scanned after 15 days instead of 14 days due to occupied CT scanner. Desorption was measured in room climate 23º–25ºC after 1, 3 and 5 days for the specimens with butt end down and 2, 4 and 6 days for the specimens with butt end up. After absorption and desorption, the same test objects were oven-dried at 103ºC and CT scanned again to obtain dry reference images which were used in the image processing.

2.3 CT scanning

A CT-scanner method was chosen, as it is a powerful tool for nondestructive measurement of density distribution and MC in wood. A CT scanner consists of an X-ray tube and a detector array that rotate around the object being examined. When the detectors have rotated around the object, a great number of X-ray absorption coefficients are calculated. 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 normalized to the corresponding linear absorption coefficient for water, μ_{water}. This normalized value is referred to as the CT-number (eq. (1)) (Herman 1980), where μ_x was the absorption coefficient for the tested material.

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

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, at Luleå University of Technology was used for measurements. The CT images were obtained using the scan settings of 110 kV, 50 mA and scan width of 10 mm. For image reconstruction a standard Shepp-Logan algorithm was used. All images were stored as 512- x 512-pixel images.

2.4 Image processing of CT images

After CT scanning, raw data images were imported into a program called Scion Image for image processing. Moisture content measurement using a CT scanner is an indirect measurement method, as the CT number couples to wood density. Two density measurements must be made to evaluate moisture content, one with unknown MC and one with known reference MC level. Wood swells and shrinks during absorption and desorption, and therefore the images must be geometrically transformed. An image-processing program for geometric transform of images such that the conditioned cross-section (after test) will appear to be identical to the immersed cross-section (before absorption) was used (Lindgren 1992). Transformed images were then subtracted from the dry reference images to determine MC. 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 FSP and ±4% (α-level of 0.05) above FS in a 7- x 7-pixel area (approx. 3 x 3 mm) can be expected (Lindgren 1992).

Thresholding of digital images was used to evaluate heartwood content and average capillary water height (CWH) by reducing the greyscale image to two levels—white and black. When measuring CWH, a CT-number corresponding to MC 40% was chosen as threshold between "low" water uptake and "high" water uptake. The border between heartwood and sapwood (L_{s1} and L_{s2} in Figure 3) was measured in images after 14/15 days absorption. The same border was used for all images from the same test object. In a few test objects borders were difficult to define due to knots close to the surface or small differences in height between sap- and heartwood.

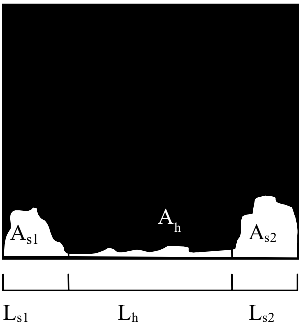


Figure 3. Threshold CT images showing average CWH (MC ≥ 40%) in end grain of spruce specimen. White areas correspond to wood that has absorbed water. Black corresponds to dry wood

2.5 Heartwood content

The heartwood content (C) was determined according to the areas (A) on the stem disc using eq (2).

$$C = \frac{A_{heartwood}}{A_{tot}} \qquad (2)$$

2.6 Average capillary water height

The average CWH, (average altitude above the bottom end grain) was determined for sapwood ($S_{average}$) according to eq. (3) and for heartwood (H), according to eq. (4). The ratio, R, between CWH in heartwood and sapwood was determined according to eq. (5).

$$S_{average} = \frac{\left(\frac{A_{s1}}{L_{s1}} + \frac{A_{s2}}{L_{s2}}\right)}{2} \qquad (3)$$

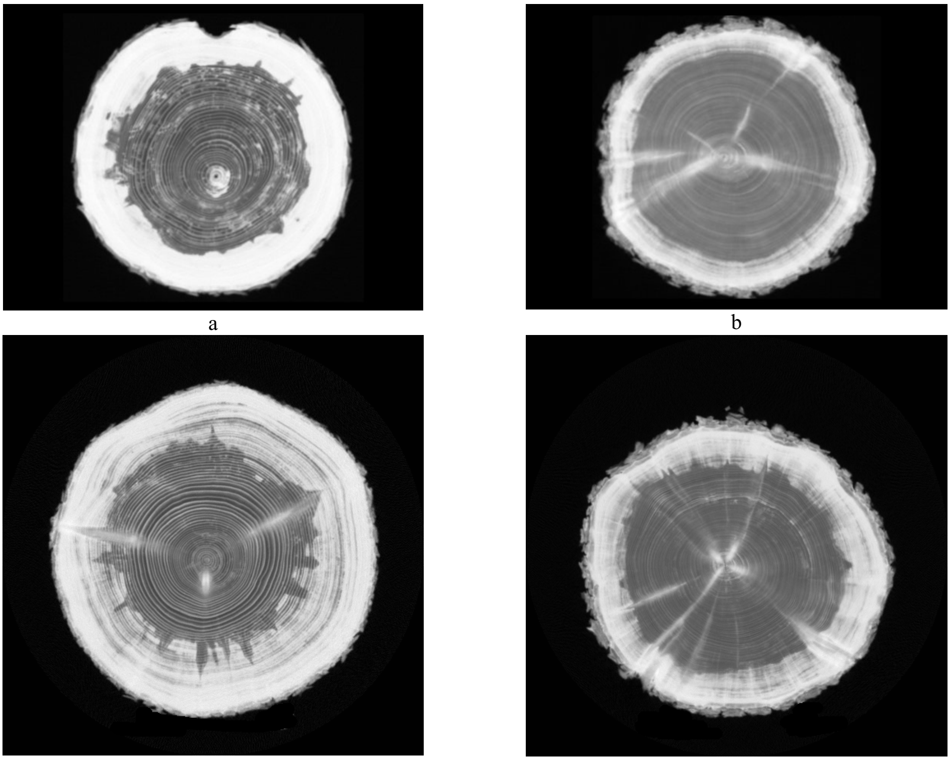
$$H = \frac{A_h}{L_h} \qquad (4)$$

$$R = \frac{H}{S_{average}} \qquad (5)$$

3 RESULTS AND DISCUSSION

3.1 Heartwood content

Figure 4 shows cross-sectional CT images of stem discs in fresh state 250 mm from butt cut. Greyscale distribution shows variation in green density of the heartwood (dark grey) and the sapwood (white). Heartwood was irregular close to the butt cut, but became more concentric towards the top of the tree.



a b c d

Figure 4. Cross-sectional CT images of stem disc in fresh state 250 mm from butt cut. Observe that the diameter varies between the stems. (a) Suppressed spruce growing with good supply of water. $Area_{heartwood}/Area_{tot}$ = 0.52, $Diameter_{tot}$ = 187 mm, $Diameter_{heartwood}$ = 128 mm. Age 65 years. (b) Suppressed spruce growing on dry site. $Area_{heartwood}/Area_{tot}$ = 0.64, $Diameter_{tot}$ = 174 mm, $Diameter_{heartwood}$ = 145 mm. Age 145 years. (c) Dominant spruce growing with good supply of water. $Area_{heartwood}/Area_{tot}$ = 0.42, $Diameter_{tot}$ = 350 mm, $Diameter_{heartwood}$ = 222 mm. Age 65 years. (d) Dominant spruce growing on dry site. $Area_{heartwood}/Area_{tot}$ = 0.56, $Diameter_{tot}$ = 338 mm, $Diameter_{heartwood}$ = 226 mm. Age 153 years.

Spruces that had been growing on a dry site had a significantly larger amount of heartwood than the trees from the wet site. The difference in heartwood content (group mean value) between dry site and wet site was evaluated with Student's t-test (α-level of 0.05). The difference is shown in Figure 5. There was no significant difference in group mean value between heartwood content in butt log and middle log (α-level of 0.05).

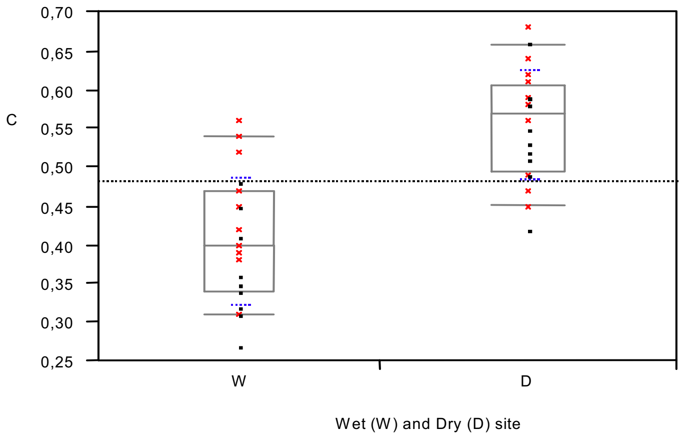


Figure 5. Heartwood content in trees grouped by growth site (wet site and dry site). The box plot shows the median value and the spread from 39 observations (butt and middle log).

Even though there were few test objects (20 from the butt log and 19 from the middle log), the results showed a strong significant difference in heartwood content between sites. Trees from the dry site were more than twice as old as the other group even though they had approximately the same diameter. Heartwood percentage often increases in direct proportion to the age of the tree for many wood species (Hillis 1987). In a Swedish investigation (Eneroth 1922) the average heartwood content in spruce was 40% when the trees were 70 years old and 58% after 150 years. Those figures agree very well with the data in this investigation. In the same report one could see that the spread was very large. For example, after 120 years the average heartwood content was 55% with a maximum value of 78% and minimum value of 30%. After 130 years, spruce attained maximum heartwood content of 90%.

3.2 Visual evaluation of butt log

A visual qualitative evaluation of the images shows differences, but also similarities, between the images (see Figure 6, Figure 7 and Figure 8). Variations in water absorption appear as different intensities in the greyscale where white areas indicate a high density due to absorption of water. Between heartwood and sapwood there is a clear boundary of water absorption after 14 days.

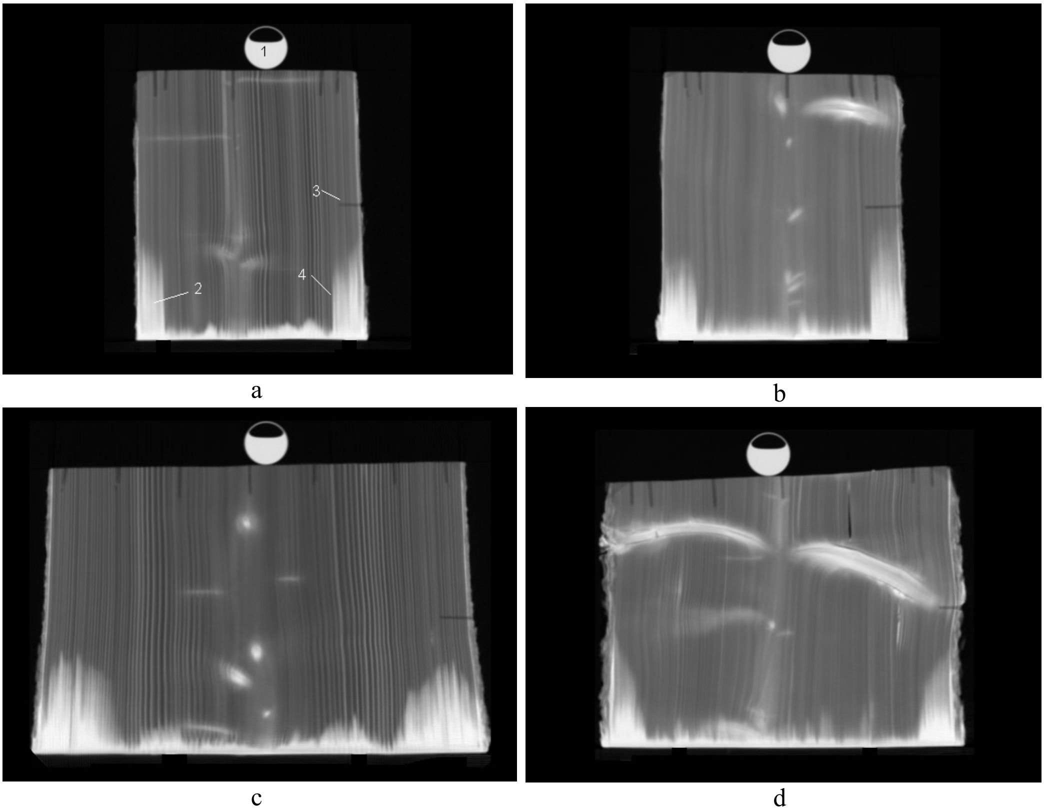
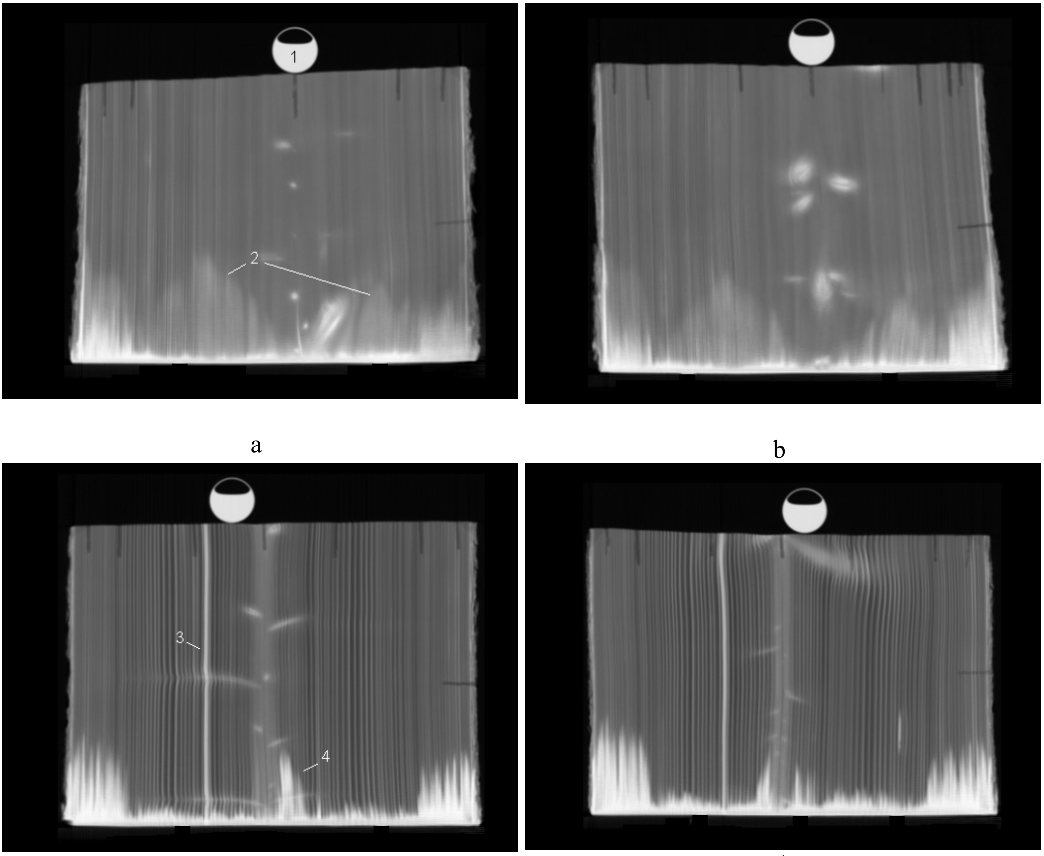


Figure 6. Vertical cross-section CT images showing absorption after 14 days in water. On top of the test objects is a jar with water as reference (1). The intensity is proportional to the amount of water. White areas indicate increased water content (2). Dark streaks on the right side of the images show a reference point, 100 mm from the bottom, on the north side of the stem (3). Between heartwood and sapwood there is a clear boundary of water absorption (4) Test objects that have grown (a) suppressed with good supply of water (wet); (b) suppressed without free ground water (dry); (c) dominant with good supply of water; (d) dominant without free ground water.

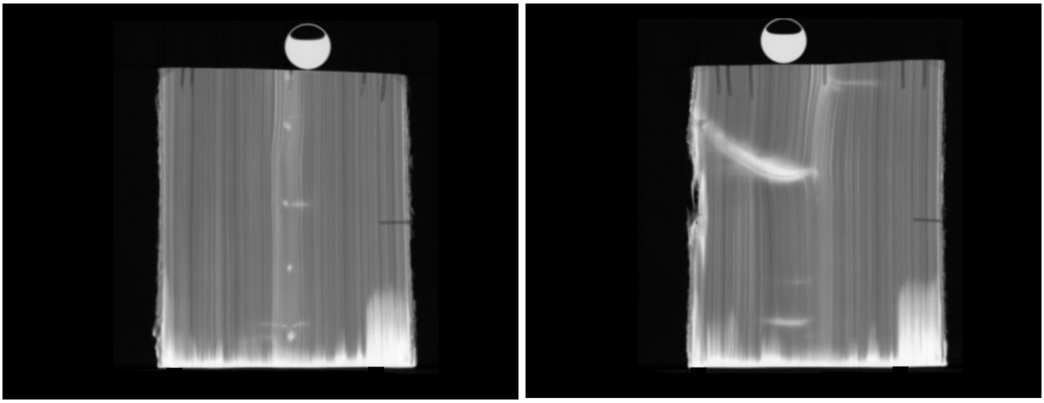
No systematic difference in (CWH) could be seen between test objects whether the top end or the butt end of the objects was immersed in water. In Figure 7a and b one can see a large area (2) with increased moisture content (MC $\geq$ 40%) in heartwood. These two were the only test objects that behaved this way. Figure 7c and d show a vertical white streak (3) in the wood and increased water around the pith (4). The white streak was dense compression wood in one annual ring vertical along that stem and did not extend east and west in the stem.



a b c d

Figure 7. CT images showing capillary water height behavioural pattern after 14/15 days in water. 1 shows a reference jar containing water. Test objects in a) and c) stand with the butt end in water and in b) and d) with top end in water. 2 shows increased moisture content (MC still below 40%) in heartwood. 3 shows dense compression wood and 4 shows increased water around the pith caused by rot. Test objects: a) dominant without free ground water, butt end down; b) dominant without free ground water absorption 15 days, butt end up; c) dominant good supply of water absorption 14 days, butt end down; d) dominant good supply of water, absorption 15 days butt end up.

CWH behavioural patterns usually vary like a wave around the stem. In general, they differ by a few millimetres between north and south. A rather extreme example is shown in Figure 8. The difference in this tree depends on a scar on the south side of the stem.



a b

Figure 8. a) and b) show difference in capillary water height patterns between south and north side of the stem caused by a scar. The objects are suppressed, grown without free ground water (dry): a) butt end down, absorption 14 days; b) butt end up, absorption 15 days.

3.3 Average capillary water height

The average CWH was measured on images from the middle board (with pith) in south-north direction when MC ≥ 40%. Specimens in Figure 7 a and b are not included in the test due to extreme deformation during drying at 103˚C. A matched paired Student's t-test showed that no significant difference in average CWH exists between test objects standing with butt end down or butt end up in water (α-level of 0.05). The difference in water uptake was greatest between heartwood and sapwood. In general, CWH in heartwood was about 1/3 of that in sapwood (MC ≥ 40%), (see Table 2).

Table 2. Ratio between CWH heartwood/sapwood (MC ≥ 40%), mean values and standard deviation in brackets. 38 observations.

Time (days)	1 day	3 days	7 days	14/15 days
Heart-/Sapwood CWH	0.26 (0.10)	0.29 (0.12)	0.33 (0.11)	0.33 (0.10)

The ratio between CWH in heartwood and CWH in sapwood showed a significant difference between the specimens from the "wet dominant" group and the other groups (see Figure 9).

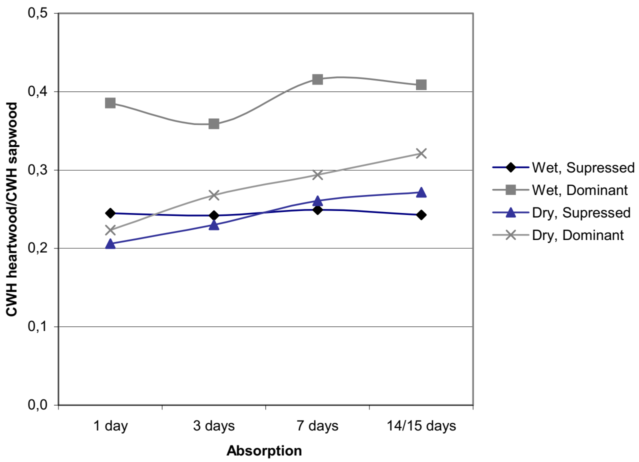


Figure 9. Ratio of average CWH heartwood to average CWH sapwood.

The average CWH in sapwood from absorption during 1 day to 15 days for the different test groups can be seen in Figure 10.

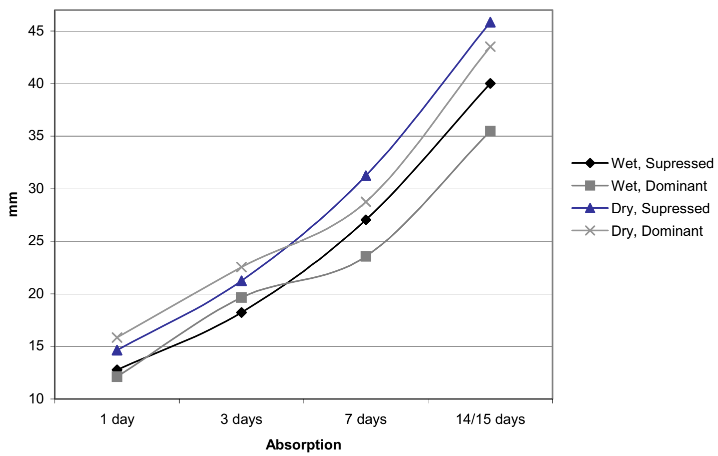


Figure 10. Average capillary water height in sapwood (MC ≥ 40%) related to test groups.

The specimens from the ”wet dominant” and the “wet suppressed” groups showed the lowest average CWH in sapwood. The difference between the groups increased with time. After one day’s absorption there was a significant difference between specimens from the “dry dominant” group and the “wet dominant" group (paired Student’s t-test, α-level of 0.05). There was a significant difference in CWH for sapwood between the specimens from the “wet dominant” group and specimens from both the “dry suppressed” group and the “dry dominant” group during absorption for 7 days and 14/15 days (paired Student’s t-test, α-level of 0.05).

The average CWH in heartwood after absorption for 1 day to 15 days related to test groups can be seen in Figure 11.

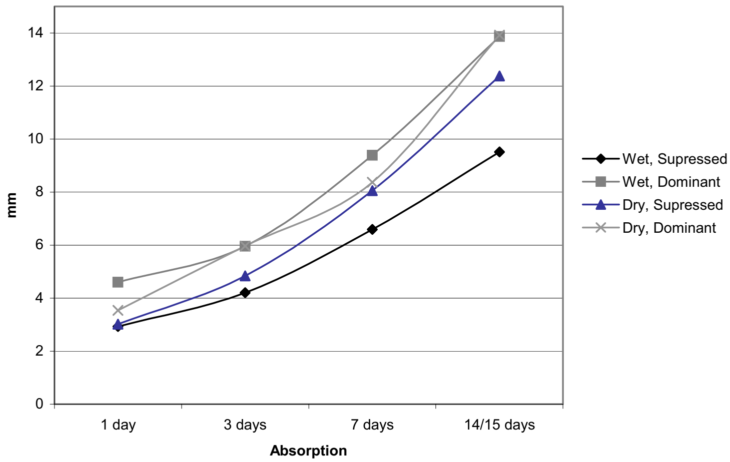


Figure 11. Average capillary water height in heartwood (MC ≥ 40%) related to test groups.

The specimens from the "wet suppressed" and the "dry suppressed" groups showed the lowest CWH in heartwood. The differences and the spread between the groups increased with time. There was a significant difference after 24 hours between the "wet dominant" group and specimens from both "wet suppressed" and "dry suppressed" groups (paired Student's t-test, α-level of 0.05). After 3 days there was a significant difference between specimens from the "wet suppressed" group and specimens from both "dry dominant" and "wet dominant" groups (paired Student's t-test, α-level of 0.05). A significant difference in CWH in heartwood could be found between specimens from the "wet suppressed" and all other groups during absorption for 7 and 14/15 days (paired Student's t-test, α-level of 0.05). Average CWH for sapwood and heartwood can be found in Table 3.

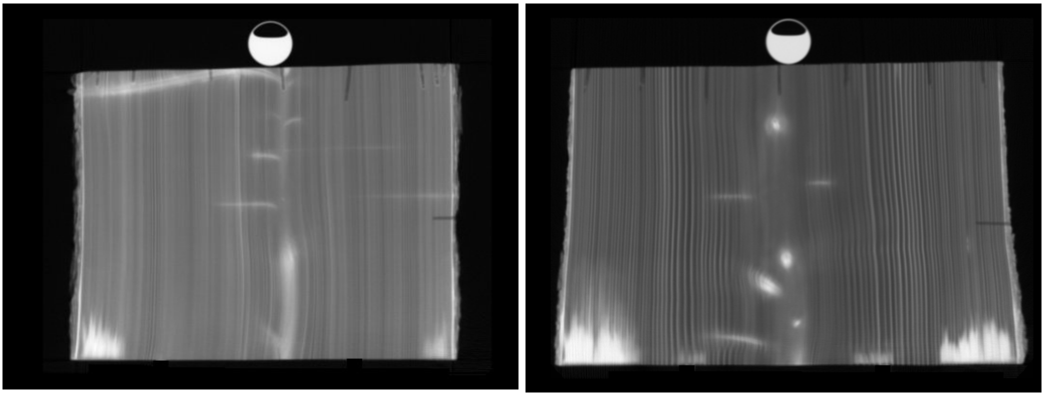
Table 3. Average capillary water height (mm) in spruce when MC ≥ 40%, mean values and standard deviation in brackets. 38 observations.

Time (days)	1 day	3 days	7 days	14/15 days
Sapwood	13.9 (3.4)	21.0 (6.3)	27.8 (6.3)	41.5 (8.4)
Heartwood	3.4 (1.3)	5.6 (1.5)	8.6 (1.7)	13.3 (2.6)

The figures can be compared to an investigation by Sell (1976). Sell measured the CWH in spruce to 10 mm parallel with the fibres and 0.2 mm perpendicular to the fibres after 24 h. The heartwood and sapwood were not separated.

3.4 Desorption

Test objects were measured with a CT scanner during desorption in room climate for 6 days. Before testing, the test objects had been standing in water for 14 days (with butt end down) or 15 days (with butt end up). After 5 days all test objects had reached MC<40% in heartwood except specimens from the "wet dominant" group (see example Figure 12 b). Sapwood needed about two more days to reach MC < 40%.



a b

Figure 12. Desorption after 5 days in room climate. Heartwood reached MC < 40% faster than sapwood after absorption for 14/15 days. Sapwood dried unevenly between north and south side of the stem. The trees had been growing a) dominant in a dry site, b) dominant in a wet site.

4 CONCLUSIONS

The most important findings in this investigation were:

- The largest difference in average CWH was between heartwood and sapwood (MC ≥ 40%). The average CWH was approximately 3 times as high in sapwood as in heartwood.
- There was no significant difference in capillary water height (CWH) between test objects absorbing water with butt end down or up (MC ≥ 40%).
- The amount of heartwood depended on growth site. Trees that had grown in an area without free water (dry) were more than twice as old and had higher heartwood content than the ones from moist forestland (wet) with a good supply of water.
- The differences and spread in CWH between the groups “wet dominant”, “wet suppressed”, “dry dominant” and “dry suppressed” increased with time.
- There was a significant difference in CWH for sapwood between specimens from the “wet dominant” group and specimens from both the “dry suppressed” and “dry dominant” group during absorption for 7 days and 14/15 days.
- There was a significant difference in CWH for heartwood from group the “wet suppressed” and all other groups during absorption for 7 and 14/15 days.
- After 5 days in room climate all test objects were dry in heartwood except for the “wet dominant”. Sapwood still had wet areas and needed about two more days to dry.
- Test objects from the “wet dominant” group showed the lowest CWH in sapwood, but dried slowly. It seems as if a low CWH does not guarantee the fastest desorption. The quantity of water and the wood structure must be considered as well. The times for desorption probably affect the possibility of wood to be attacked by fungi due to environmental conditions. Therefore, the behaviour of desorption is an interesting area to investigate further in the future.
- CT scanning has earlier been proven to be a suitable technique for measurement of internal features in wood. This study shows that it is also possible to follow changes during absorption and desorption with good accuracy. In future work the middle log will be examined and compared to the butt log.
- Finding parameters that affect water absorption is a complex problem. Many parameters can affect absorption and interact with each other. Therefore, interesting parameters such as resin content, age, density, diameter, etc., will be evaluated with multivariate analysis in the future.

5 ACKNOWLEDGEMENTS

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II

Measurement of spruce moisture gradients using CT scanning during three cycles of liquid water absorption and desorption in end grain

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Abstract

The object was to examine how growth parameters explain differences in water absorption in Norway spruce *(Picea abies (L.) Karst.*). The hypothesis was that these differences influence the durability of building products, since microorganisms in wood generally need a moisture content higher than 20% in order to survive. By choosing wood in a systematic way, it should be possible to increase product life span and decrease the amount of maintenance required for spruce products used outdoors above ground. A repeated absorption and desorption cycle was performed in order to observe changes in moisture content distribution over time. Logs from 20 trees, half of them suppressed and half of them dominant, were taken from two sites at a research site close to Vindeln in the north of Sweden. One site had a good supply of free water (wet) and the other site was without free ground water (dry). The logs were sawn (through and through) into boards and dried to 12% moisture content. In order to evaluate absorption, wood density and moisture content were measured by computed tomography (CT) scanning and image processing. The measurements were performed in room climate, and the test pieces were CT scanned, after 1, 3, 7 and 14-15 days of liquid water absorption in end grain and during desorption in room climate. The absorption and desorption cycles were repeated 3 times. Moisture gradients were measured in the sapwood and heartwood on the south side of the stem.

- The following results were obtained:There was a large difference in water absorption between heartwood and sapwood.
- During absorption in sapwood, the moisture content gradients decreased from cycle 1 to cycle 3, which was a prominent feature after 14 and 15 days of absorption. The capillary water height ($CWH_{20\%}$) was estimated as the distance where the MC gradient reached 20%. The $CWH_{20\%}$ decreased from cycle 1 to cycles 2 and 3. The MC close to the surface was approximately the same during all cycles at the same time interval.
- During absorption in heartwood, the moisture content gradients followed almost the same curve for cycles 1, 2 and 3. The behaviour of the surface was the same as that of sapwood in regard to MC level.
- During desorption, heartwood dries faster than sapwood, but heartwood starts from a lower MC level.
- During desorption, drying in cycle 3 is faster than in cycles 1 and 2 for both sapwood and heartwood.

1. Introduction

The task was to investigate moisture content (MC) gradients during liquid water absorption and desorption when the cycle was repeated 3 times. The purpose was to examine whether the MC stayed the same, increased or decreased between the cycles in order to be better able to come to a conclusion about long-term effects on durability. With CT scanning and image analysis it is possible to measure and follow MC distribution and gradient changes of moisture content over time with known time intervals. The durability of wood products depends not only on their resistance to microorganisms but also on the tendency of wood to absorb rainwater by capillary action Sell [10]. Wood absorbs water 1000 times faster by direct contact than by diffusion in vapour phase Holbrow et al. [6]. Microorganisms, mainly fungi and bacteria, have different requirements on the environment in order to live and propagate. Generally one could say that optimal MC for wood-rotting fungi is between 28% and 45% in the wood and optimal temperature is between 25° and 32°C. The hypothesis is that differences in water absorption and desorption in the end grain cause differences in durability for building products, since microorganisms in wood need enhanced MC to cause degradation. Damage due to rot on constructions commonly occurs in the end grain close to the surface or sometimes a distance into the wood. Apart from durability, water absorption also affects dimensional change and strength. Therefore it is important that wood should not absorb capillary water in the end grain and that it has the capacity to dry out during favourable weather conditions.

Earlier investigations have been done of fluid flow measured as permeability. The permeability of wood is a measure of the ease with which fluid flows through wood in response to pressure gradients. Liquid movement from one tracheid to another in coniferous wood is largely dependent upon the bordered pit pairs Bailey [1], Côté & Krahmer [4], Wardrop & Davies [12]. During drying, however, these pits aspirate, resulting in a marked reduction in permeability Comstock & Côté [3]; Côté & Krahmer [4]. It was observed that as permeability decreases, so does the rate of flow over time. Kelso et al. [7] determined that air blockage was largely responsible for the decrease in flow rate. Chen & Hossfeld [2] demonstrated that when the direction of liquid flow was repeatedly reversed, a constant value, the same in both directions, was approached. Resch & Ecklund [9] indicated that the liquid was physically plugging the specimen with contaminants, since successive dryings after liquid flow showed a continual decrease in gas permeability. Stamm [11] found that the maximum lumen radius is greater for sapwood than for heartwood, and the same trend was found for the maximum fiber length. Since heartwood contains considerably smaller effective pit pores than sapwood, there is considerably greater drying tension on the pit pores, which in turn could result in more pit aspiration.

1.1 CT scanning

A CT scanner is a powerful tool for nondestructive measurement of density distribution and MC in wood. A CT scanner consists of an X-ray tube and a detector array that rotate around the object being examined. After rotation, a large number of X-ray absorption coefficients are calculated. 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 normalized to the corresponding linear absorption coefficient for water, μ_{water}. This normalized value is referred to as the CT number Herman [5], where μ_x was the absorption coefficient for the tested material (eq. (1)).

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

By assigning each CT number a certain greyscale value, an image can be evaluated showing the density variation within a slice of the object.

1.2 Image processing

Moisture content measurement using a CT scanner is an indirect measurement method, as the CT number couples to density of wood and water. Two density measurements must be made in order to evaluate moisture content, one with unknown MC and one with known MC level as a reference measurement. In this case the reference level was established when the test objects had been oven-dried at 103°C. Wood swells and shrinks during absorption and desorption, and therefore the images must be geometrically transformed if they are 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 reference cross-section was used Lindgren [8]. Transformed images were then subtracted from the dry reference images to determine MC. The accuracy of the 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 fiber saturation point (FSP) and ±4% (α-level of 0.05) above FSP in a 7- x 7-pixel area (approximately 3 x 3 mm) can be expected Lindgren [8].

2. Materials and methods

2.1 Materials

Twenty trees of Norway spruce (*Picea abies* (L). Karst.), half of them suppressed and half of them dominant, were taken from two sites. The trees were grown at a research site close to Vindeln in the north of Sweden. One site had a good supply of water, and one site was without free ground water. The spruces from the dry site were grown on a typical ”sandy heath” 175 m above sea level with an average age of 148 years. The dominant trees had an average diameter of 29 cm at breast height, and the suppressed trees an average diameter of 18 cm. The spruces grown on “moist forestland” 250 m above sea level had an average age of 67 years. The dominant trees had an average diameter of 31 cm at breast height, and the suppressed trees an average diameter of 19 cm. Different characteristics for the four test groups are shown in Table 1.

Table 1. Data for the test trees. Mean value of five trees in each group.

Test group	Age (years)	Growth ring width (mm)	Density ($MC_{12\%}$) (kg/m^3)	Breast height diameter (cm)	Height (m)
Wet suppressed	67	1.5	407	19	18.3
Dry suppressed	137	0.6	484	18	14.3
Wet dominant	66	2.6	378	31	21.8
Dry dominant	158	1.0	440	29	22.2

The trees were cut into 5-meter logs. The logs were sawn through and through in north-south direction to 32-mm-thick boards and dried to 12% MC. Test objects for absorption testing were cut from the butt ends of the logs. They were approximately 0.2 m in height taken 1 m from the butt cut. All objects were mounted with the butt end up during measurements. The test objects were placed in a climate of standard conditioning RH 65% and temperature 22ºC (corresponding approximately to MC 12%) for more than two months. The sawn flitches from the same height of the tree were assembled with a distance of 12 mm into a single test object (see Figure 1).

(1) 

Figure 1. To ensure correct repositioning in the CT scanner, lasers were used to mark vertical reference points 100 mm from the end grain. A 3-mm-diameter drill was used to make the holes.

2.2 Absorption and desorption of water

Test objects were placed in a basin on bars of stainless steel in 5-mm-deep tap water for end grain absorption. The measurements were performed in room climate with the aid of a CT scanner. Table 2 shows times for CT scanning in the absorption/desorption cycles chosen.

Table 2. Absorption and desorption cycles

	Absorption (days)				Desorption (days)					
Cycle 1	1	3	7	15	2	4	6			
Cycle 2	1	3	7	14	1	2	3	6		
Cycle 3	1	3	7	14/15	1	2	3	4	5	7

The scan followed the grain in the middle of each board and was 10 mm wide. Desorption was measured in room climate 22°–25ºC. The test objects were laid on their sides during drying. After absorption and desorption, the same test objects were oven-dried at 103ºC and CT scanned again to obtain dry reference images for MC measurement.

2.3 CT scanning

A CT scanner, Siemens SOMATOM AR.T, at Luleå University of Technology was used for the measurements. The CT images were obtained using the scan settings of 110 kV, 50 mA and scan width of 10 mm. For image reconstruction, a standard Shepp-Logan algorithm was used. All images were stored as 512- x 512-pixel images.

2.4 Image processing of CT images

The measurements were performed on the sapwood and heartwood mainly on the south side of the stem (to the left in the images, see Figure 2). When there were anomalies such as knots, the measurements were done on the north side. The CT image in Figure 2 shows absorption after 15 days in water.

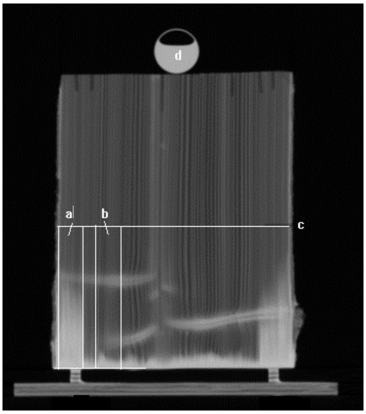


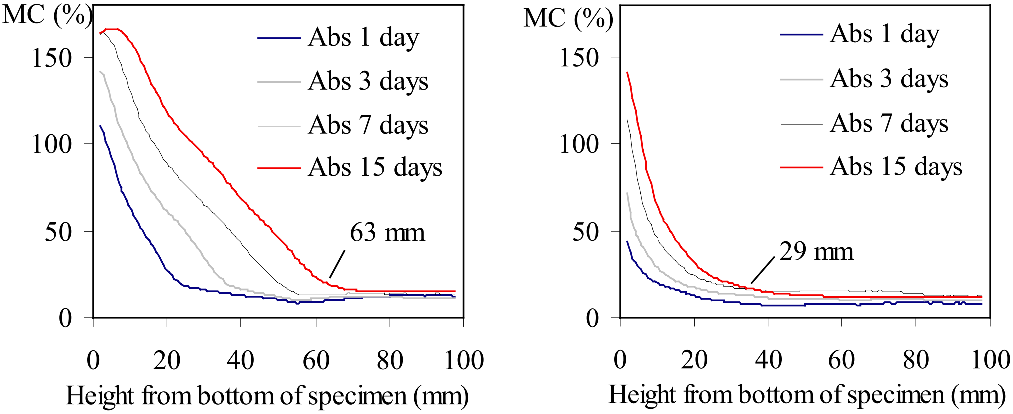
Figure 2. A vertical cross-section CT image showing absorption after 15 days in water. The letters a and b show where the gradients were measured in sapwood and heartwood. The gradients in heartwood were measured 12 mm from the sapwood borderline. The letter c is a reference line 100 mm from the bottom surface, and d is a reference jar containing water.

The intensity is proportional to the amount of water. White areas indicate increased water content. Between heartwood and sapwood there is a clear boundary of water absorption. 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. The first 2 pixels (approximately 1.4 mm) close to the bottom edge were removed to eliminate artifacts. A smoothing function was applied to the gradients based on the average of 11 pixels. The smoothing function smoothes the variation of the annual rings. The measurements of MC level at surface (MC_{surf}) were an average of the first 5 pixels. The capillary water height (CWH) was chosen as the distance from surface to the point where MC reached 20% ($CWH_{20\%}$).

3. Result and Discussion

3.1 Absorption

Large differences in water absorption and desorption were observed between heartwood and sapwood, as can been seen in Figure 2 and Figure 3. In the example, the capillary water height ($CWH_{20\%}$) was 63 mm in sapwood after absorption for 15 days (in cycle 1, see Figure 3a). The corresponding value for the heartwood in Figure 3b was 29 mm.

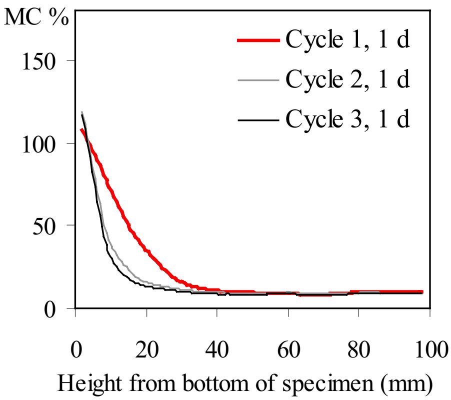


a b

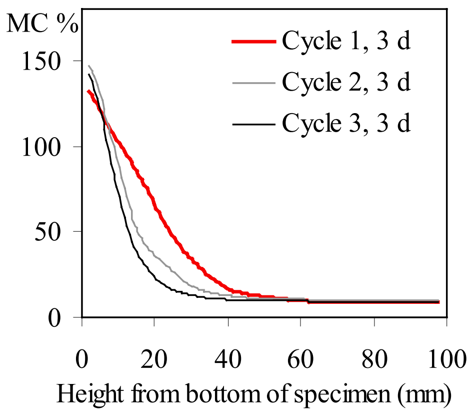
Figure 3. Moisture content profiles during absorption for 1 to 15 days in cycle 1. Specimen from "dry suppressed" group: a) sapwood; b) heartwood

3.1.1 Sapwood

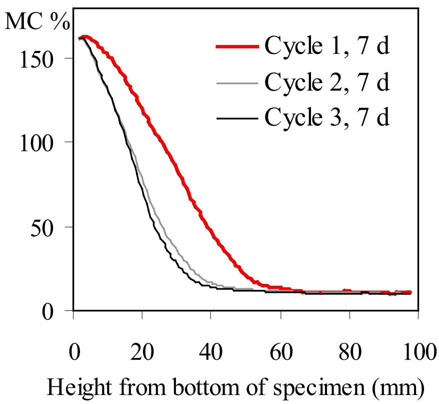
During absorption in sapwood, the moisture gradient levels decreased from cycle 1 to cycle 3. In general, cycle 1 is distinctly different from cycles 2 and 3, which are quite similar to each other. However, the water absorption front recedes towards the bottom of the specimen to the left as seen in the Figure 4. This was especially clear after 14/15 days of absorption. The cycle 1 gradients cross the other gradients at 1 day and 3 days, but after 7 days all gradients start at approximately the same MC level.



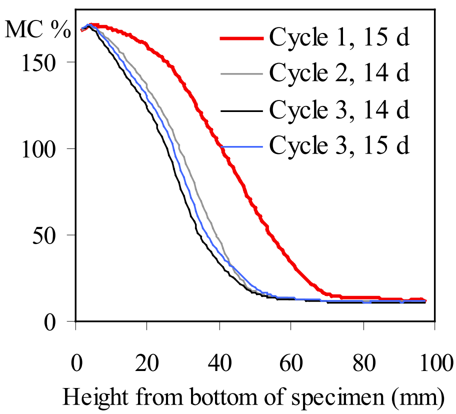
a



b



c



d

Figure 4. MC gradients after absorption for 1, 3, 7 and 14/15 days in sapwood. Specimen from "wet dominant" group: a) absorption 1 day; b) absorption 3 days; c) absorption 7 days; d) absorption 14/15 days.

MC_{surf} closest to the surfaces increased with time (see Table 3). It can be observed that the moisture content level closest to the surfaces (MC_{surf}) stays about the same throughout the 3 cycles within the same time interval. $CWH_{20\%}$ decreased from cycle 1 to cycles 2 and 3 after 3, 7 and 14/15 days.

Table 3. Average MC close to the surface (MC_{surf}) and average $CWH_{20\%}$ measured in sapwood. Standard deviation in brackets.

Absorption	3 days		7 days		14/15days	
	MC_{surf} (%)	$CWH_{20\%}$ (mm)	MC_{surf} (%)	$CWH_{20\%}$ (mm)	MC_{surf} (%)	$CWH_{20\%}$ (mm)
Cycle 1	120 (13)	35 (8)	153 (12)	49 (11)	162 (10)	63 (9)
Cycle 2	123 (13)	31 (11)	148 (11)	42 (12)	161 (9)	52 (9)
Cycle 3	124 (11)	28 (9)	149 (9)	40 (11)	161 (10)	56 (11)

3.1.2 Heartwood

In heartwood the gradients from cycles 1, 2 and 3 followed almost the same (steep) gradient during absorption, as seen in Figure 5.

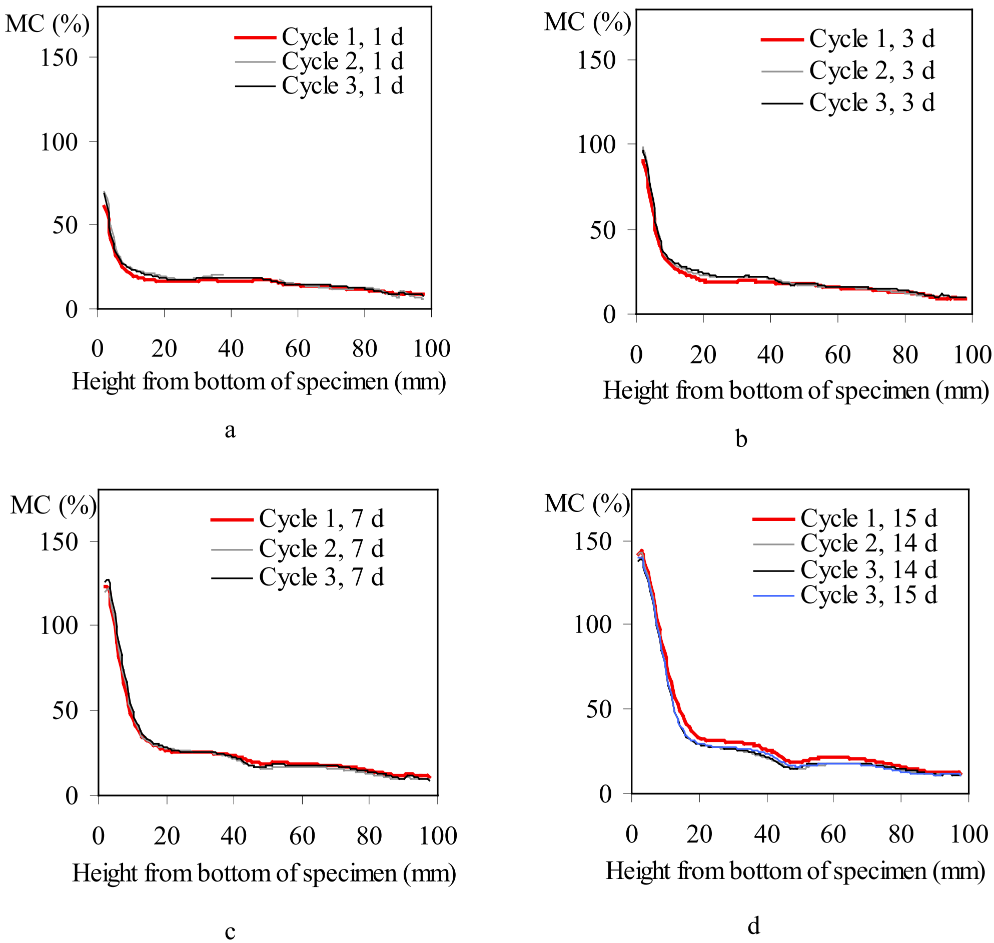


Figure 5. Absorption gradient. 3 cycles of absorption for 1, 3, 7 and 14/15 days in heartwood. Specimen from "dry suppressed" group: a) absorption 1 day; b) absorption 3 days; c) absorption 7 days; d) absorption 14/15 days.

The same behavior as for sapwood of MC level at the surface can be observed (Table 4). There was no difference in $CWH_{20\%}$ between cycles 1, 2 and 3. $CWH_{20\%}$ was measured on 19 objects because of the presence of knots in one specimen.

Table 4. MC content close to the surface (MC_{surf}) and $CWH_{20\%}$ measured in heartwood. Mean values and standard deviation in brackets.

Absorption	3 days		7 days		14/15days	
	MC_{surf} (%)	$CWH_{20\%}$ (mm)	MC_{surf} (%)	$CWH_{20\%}$ (mm)	MC_{surf} (%)	$CWH_{20\%}$ (mm)
Cycle 1	76 (16)	18 (7)	108 (20)	33 (15)	133 (16)	39 (12)
Cycle 2	80 (16)	22 (11)	108 (20)	29 (13)	132 (19)	30 (11)
Cycle 3	81 (17)	20 (7)	112 (21)	30 (11)	131 (13)	33 (14)

3.2 Desorption

During desorption, heartwood MC gradients were steeper and reached below 20% MC closer to the surface than sapwood, but heartwood starts from a lower level after absorption for 14 days. There were large variations in MC gradients, but general appearances can be found in Figure 6 and Figure 7.

3.2.1 Sapwood and heartwood

During desorption, drying is faster in cycle 3 than in cycle 1 for both sapwood and heartwood, as shown in Figure 6 and Figure 7. After 2 days of desorption there are still quite large areas with increased water content, especially in cycle 1. After drying, the MC close to the surface is lower than a few millimeters into the wood.

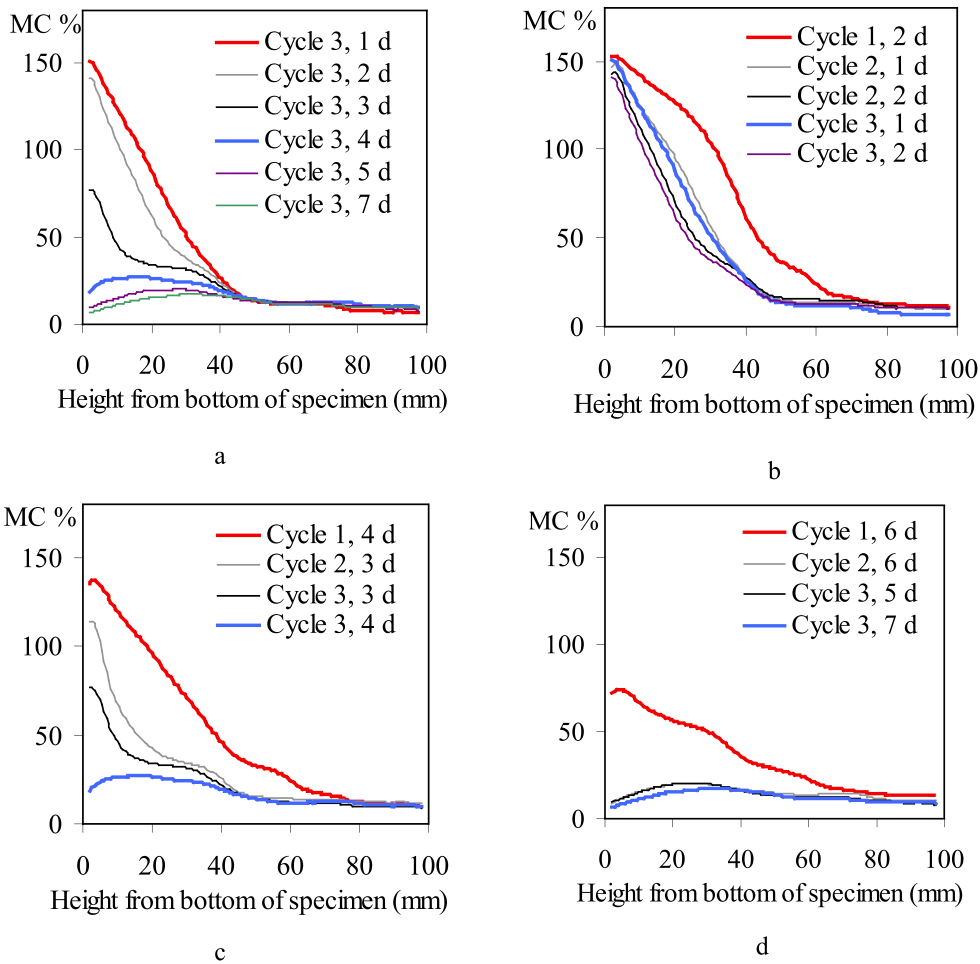


Figure 6. Desorption gradient in sapwood for 3 cycles. Specimen from “dry suppressed” group: a) desorption 1 to 7 days during cycle 3; b) desorption for 1 and 2 days, cycles 1, 2 and 3; c) desorption for 3 and 4 days, cycles 1, 2 and 3; d) desorption for 5, 6 and 7 days, cycles 1, 2 and 3.

MC_{surf} was higher in sapwood than heartwood after 2 days of desorption, as shown in Table 5. MC_{surf} decreased from cycle 1 to cycle 3.

Table 5. MC_{surf} after desorption for 2 days, sapwood and heartwood, during cycles 1, 2 and 3. Mean values and standard deviation in brackets.

Desorption 2 days	Sapwood MC_{surf} (%)	Heartwood MC_{surf} (%)
Cycle 1	149 (17)	91 (20)
Cycle 2	130 (24)	71 (21)
Cycle 3	117 (32)	51 (27)

Examples of desorption in heartwood shown in Figure 7.

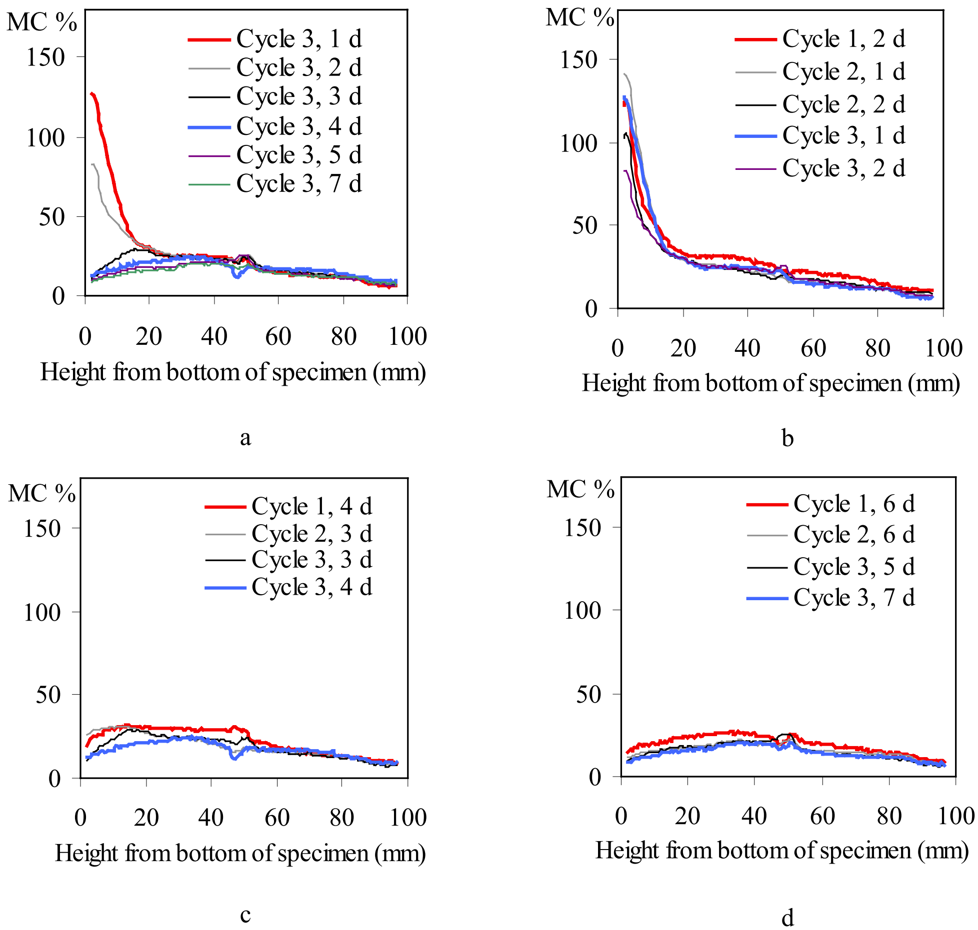


Figure 7. Examples of desorption in heartwood. Test objects from ”dry suppressed” group: a) desorption 1 to 7 days during cycle 3; b) desorption for 1 and 2 days, cycles 1, 2 and 3; c) desorption for 3 and 4 days, cycles 1, 2 and 3; d) desorption for 5, 6 and 7 days, cycles 1, 2 and 3.

3.3 Summary

In general, cycle 1 MC gradients in sapwood are distinct from those of cycles 2 and 3, which resemble each other. Water absorption fronts withdraw towards the bottom of the specimen for cycles 2 and 3, as compared with cycle 1. The capillary water height at 20% MC ($CWH_{20\%}$) was higher for cycle 1 than for cycles 2 and 3. This was most obvious after 14/15 days of absorption. Compared to sapwood, the MC gradients in heartwood were steeper at lower moisture content levels. The differences in appearance of MC gradients in heartwood were small in cycles 1, 2 and 3, which followed almost the same gradients, especially close to the surface. However, the MC close to the surface (MC_{surf}) was approximately the same for all cycles at the same time interval for both sapwood and heartwood. After desorption, cycle 3 had a lower MC_{surf} than cycles 1 and 2 for both sapwood and heartwood.

The differences between the cycles, especially in sapwood, could be due to aspiration, to air blockage from the air in the water or to water transportation of contamination and extractives that block the pits. Repeated cycles of absorption and desorption of water seem to decrease MC in wood. Fungi need water for growth. Water also affects the shrinking and swelling of wood, which in turn affects cracking. Hence a low MC is favorable from the point of view of durability. In this investigation, the wood was exposed to water that could evaporate without the impact of weathering followed by cracking and attacks from microorganisms.

MC_{surf} and $CWH_{20\%}$ were not based on curvature measurements, although the shape of MC gradients might be different and have a certain influence on long-term durability. One gradient might show a high value for $CWH_{20\%}$ and show a low value for MC_{surf}, while another MC gradient can show a low value for $CWH_{20\%}$ and at the same time show a high value for MC_{surf}. Another approach for establishing MC_{surf} and $CWH_{20\%}$ might be to evaluate the whole gradient using a multivariate method.

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III

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.

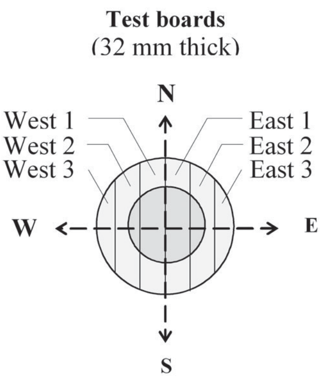

FIG. 1–Sawing pattern

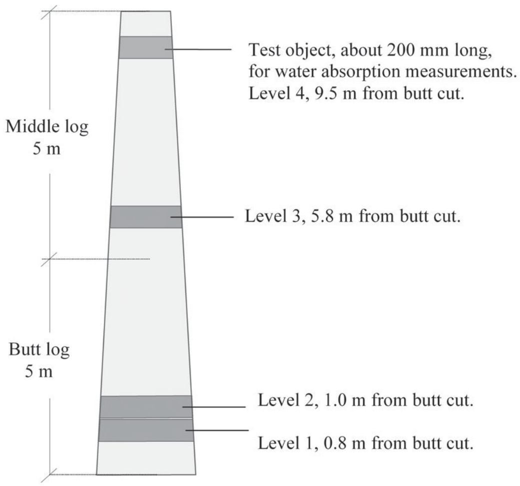

FIG. 2–How the trees were divided and where the test object was located in a stem

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.

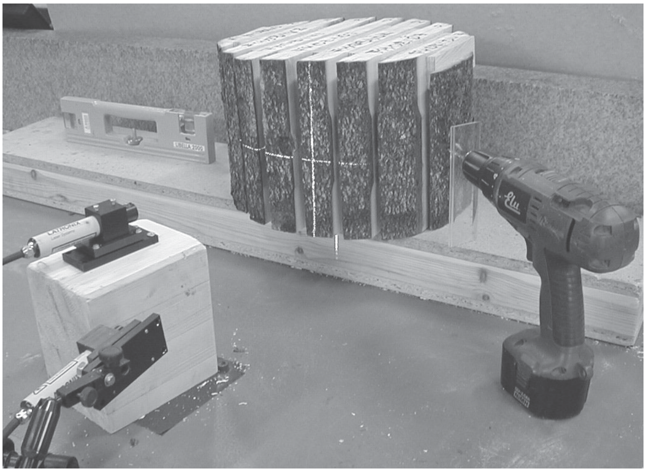

FIG. 3–Sawn flitches

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

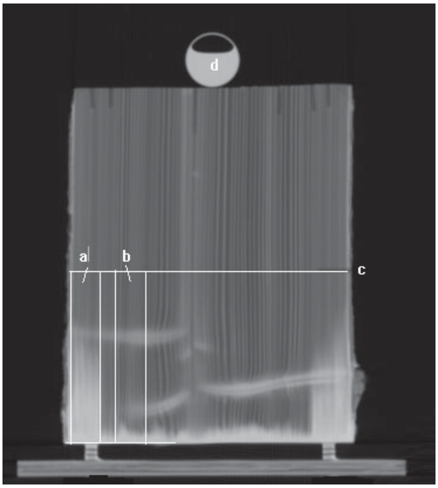

FIG. 4–A vertical cross-section CT image showing absorption after 14 days in water. Points a and b indicate where the gradients were measured in sapwood and heartwood. The gradients in heartwood were measured 12 mm from the sapwood border. Point c is a reference line 100 mm from the bottom surface, and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

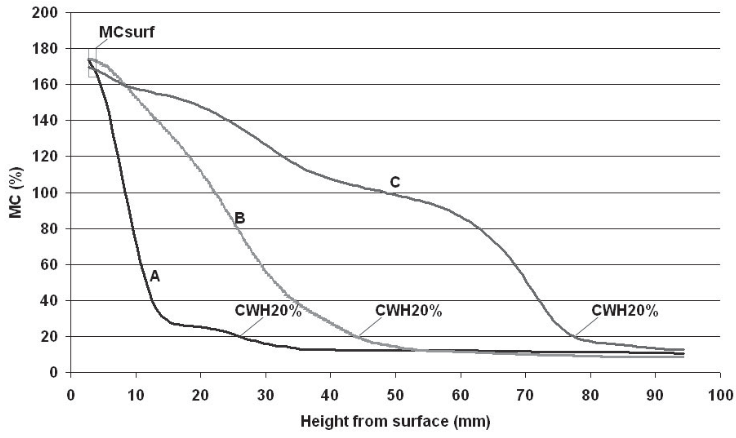

FIG. 5– Examples of three moisture content gradients (A, B, and C) after sorption of liquid water in end grain for 14 days in Norway spruce.

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).

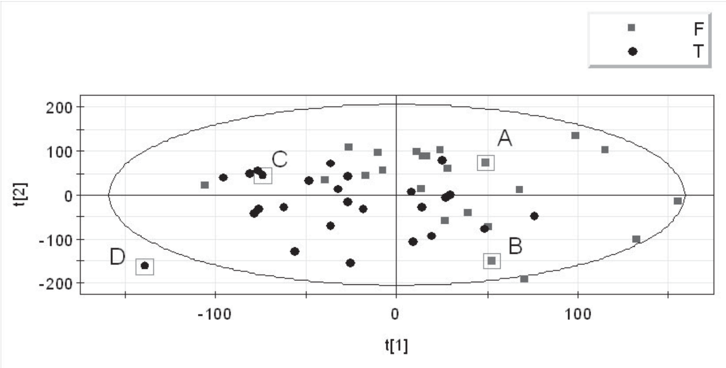

FIG. 6–Score plot for moisture content observations from the dry site (T) and the wet site (F) measured in heartwood after 14 days of absorption (Model 1). Moisture content gradients corresponding to observations are marked with rectangles.

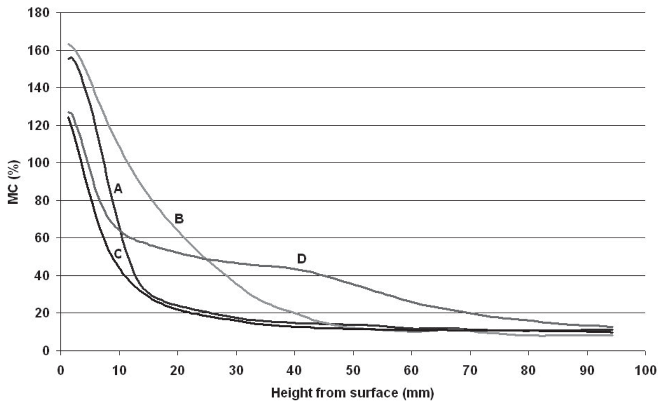

FIG.7–Moisture content gradients measured in heartwood after 14 days of sorption (*see* rectangles in Fig. 6). Observations from wet site/suppressed = A, wet site/dominant = B, dry site/suppressed = C, and dry site/dominant = D.

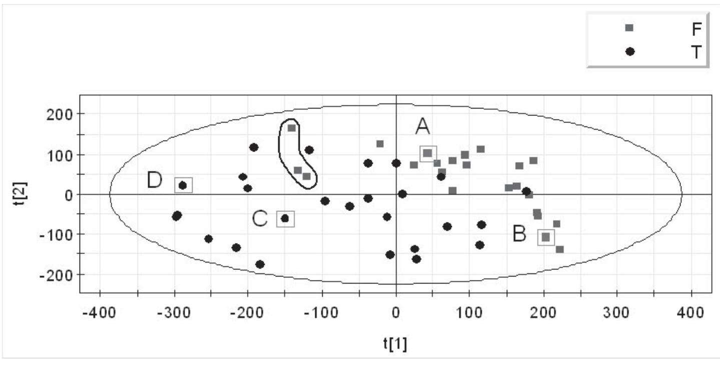

FIG. 8–To the left in score plot, observations from dry site (T) and to the right, observations from the wet site (F), after absorption for 14 days in sapwood (Model 5). Moisture content gradients corresponding to observations are marked with rectangles.

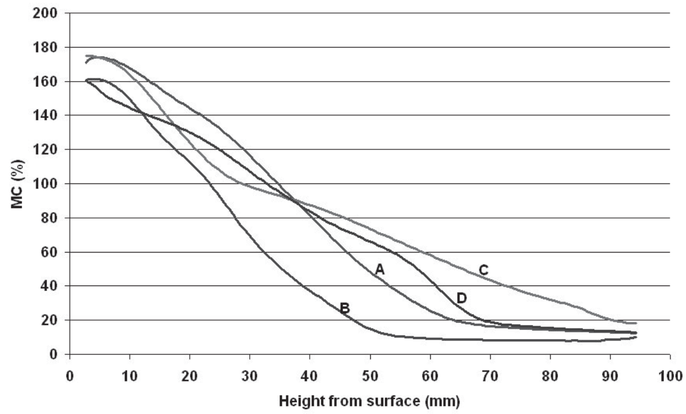

FIG. 9–Moisture content gradient in sapwood after absorption for 14 days in end grain marked in score plot (Fig. 8). Observations from A = wet site/dominant, B = wet site/ dominant, C = dry site/dominant, and D = dry site/dominant.

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.

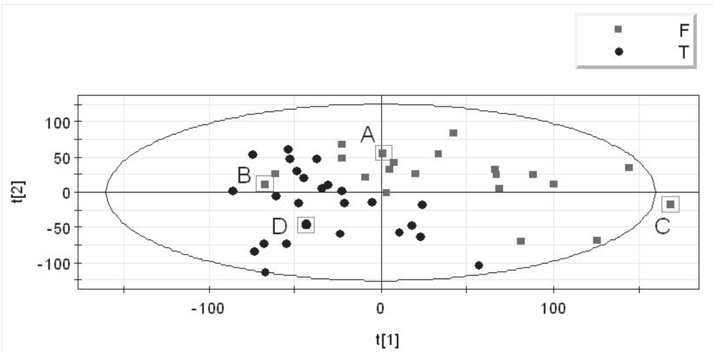

FIG. 10–Score plot for moisture content observations from the dry site (T) and the wet site (F) measured in heartwood after desorption for 3 days in room climate (Model 10). Moisture content gradients corresponding to observations are marked with rectangles.

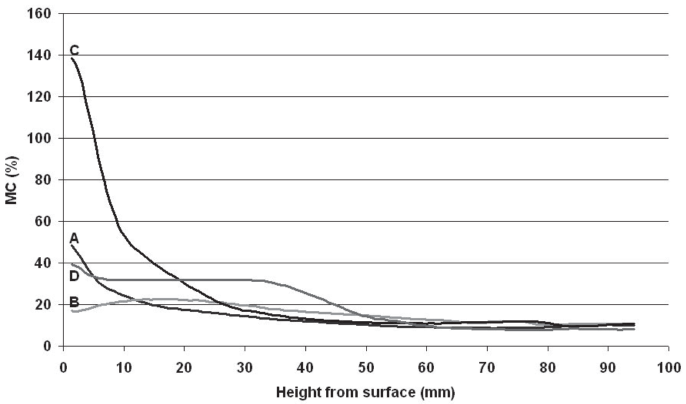

FIG. 11–Moisture content gradients in heartwood corresponding to observations marked with rectangles in Fig. 10 (A = wet site/suppressed, B = wet site/suppressed, C = wet site/dominant, and D = dry site/dominant).

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.

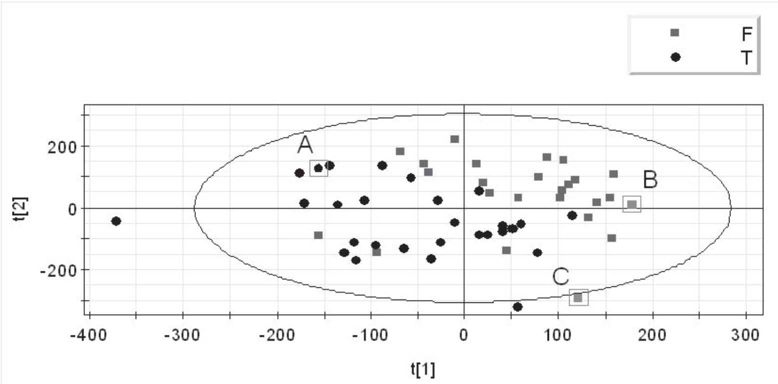

FIG. 12–Score plot (Model 15) after desorption for 3 days in sapwood (A = dry site/suppressed, B = wet site/dominant, C = wet site/dominant). Moisture content gradients corresponding to observations marked with rectangles are shown in Fig. 13.

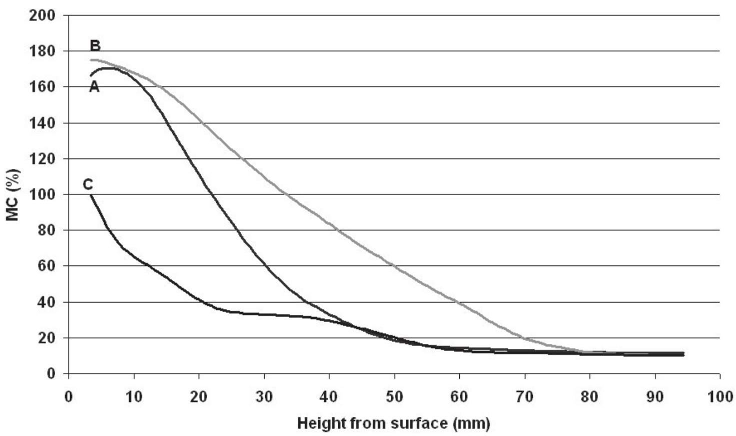

FIG. 13–Moisture content gradients in sapwood, corresponding to observations marked with rectangles in Fig. 12.

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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IV

Moisture content gradients in young spruce during liquid water sorption in end grain measured with CT scanning

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Abstract

Liquid water sorption in the longitudinal direction in wood samples of Norway spruce (*Picea abies (L.) Karst*) was measured with computed tomography (CT) scanning and image processing and then evaluated using multivariate discriminant analysis. The objective was to determine whether heartwood from young spruce has appropriate properties, in terms of low water sorption, for use in exterior products.

CT images of the cross-section of a green stem showed inhomogeneity in heartwood density (moisture content) and the border between sapwood and heartwood were diffuse. The variation in moisture content in the green stem could be divided into sapwood, heartwood and incompletely developed heartwood (intermediate wood).

Test pieces consisted of sapwood, heartwood and intermediate wood 32 mm thick and 200 mm long and dried to 12% MC. Measurements were performed after 1, 3, 7 and 14 days of liquid sorption in end grain and drying under ambient conditions. PLS-DA (discriminate analysis) models show that after sorption for 1, 3, 7 and 14 days, 71%, 71%, 78% and 77%, of the observations were predicted correctly. The MC gradients from intermediate wood were more similar to MC gradients from heartwood than sapwood during sorption and drying. MC gradients from sapwood take longer time to level out to an MC below 20% than heartwood and intermediate wood. Since capillary water height between heartwood and sapwood is small, the conclusion is that age or annual ring with of the tree must be taken into account when durable heartwood for outdoor use is chosen. Rapidly grown young spruce may be mixed with old, suppressed spruce with better properties for outdoor use.

1. Introduction

1.1 Background

For external use, timber that absorbs little water and dries fast has the right qualifications to withstand decay, since fungal attack in wood starts in the presence of water. Little water sorption leads to small differences in moisture movement and thus fewer cracks. Heartwood in many species is considered to be more durable than sapwood because it has a higher extractive content and is less hygroscopic.

In a previous investigation, it was shown that capillary water height (CWH) was about 3–4 times higher in spruce sapwood than spruce heartwood with an average age of 107 years (Sandberg 2002). A 3.5-year field test above ground showed that heartwood panels of spruce had smaller weight change over the test period, fewer cracks, shorter crack length and less discoloration from fungi (Sandberg 2006a). This indicates that heartwood of spruce might be suitable for exterior use above ground. Heartwood cannot be easily detected in dried Norway spruce, since its heartwood is uncoloured, but in the fresh state, the heartwood can be outlined in the cross-section as a paler area. With CT scanning, water distribution during capillary flow can be shown visually and is measurable by image processing. CT 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 and moisture content and be used in 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). CT scanning 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).

In CT images of fresh stem discs, heartwood and sapwood can be clearly outlined, since the greyscale in CT images is proportional to density and water content. The big variation in density in the cross-section in young trees here called intermediate wood has been observed previously in CT images, but the phenomenon has not been described nor has its possible effect on durability been explained. The purpose of this study was to determine whether the properties of young spruce make it appropriate for use in exterior products with respect to low water sorption and the impact of access to water during growth. The long-term goal is to define parameters for the quality of spruce heartwood that can be measured on-line in an industrial setting.

Young, fast growing trees were selected to cover a diameter at breast height similar to that of older, slowly growing trees (Sandberg 2002, 2006b). Good access to water can be expected to govern water distribution in the tree. Since most damage in outdoor products occurs in the longitudinal direction, since free water from rain is absorbed (through capillary flow) fastest in that direction, sorption in end grain was studied.

In the cross-section of the stem, there are three major zones: sapwood close to the bark, heartwood in the middle of the stem and, between these major zones, a narrow transition zone. The definitions of the zones are as follows.

The trunk has three functions: to conduct sap from the roots to the cambium and leaves, provide a strong and rigid stem and be a reservoir for the storage of food substances (Dinwoodie 1981). Sapwood is defined as "the portion of the wood that in the living tree contains living cells and reserve materials (e.g. starch)" (Anon. 1957).

Heartwood is "the inner layers of wood which, in the growing tree, have ceased to contain living cells and in which the reserve materials (e.g. starch) have been removed or converted into heartwood substances. It is generally darker in colour than sapwood, though not always clearly differentiated" (Anon. 1957). In spruce, heartwood starts to form close to the pith at an age of about 20–30 years.

The transition zone, also called *white zone* or *pale zone*, which can be defined as a narrow, pale-coloured zone surrounding the heartwood (or injured wood tissue), is often impermeable to liquids, with a moisture content lower than sapwood and sometimes also lower than heartwood. The transition zone often contains living cells, but is devoid of starch (Hillis 1987 and ref. therein).

Intermediate wood is defined as the "inner layers of the sapwood that are transitional between sapwood and heartwood in colour and general character" (Anon. 1957). Intermediate wood can be confused with the narrow transition zone, and the terms have been used interchangeably. Intermediate zones in *Picea abies* have been found to have a variable width of about 5–10 cm in a log cross-section and a moisture content that is lower than that of sapwood and is similar to that of heartwood. It is uncertain whether all intermediate wood contains living cells (Hillis 1987 and ref. therein).

2. Materials and Methods

2.1 Materials

Ten Norway spruce (*Picea abies (L). Karst.*) trees were sampled from two stands at Flakaliden, Vindeln Experimental Forest, belonging to the Swedish University of Agricultural Science (64º14'N, 10º 46'E) with the help of the staff. To increase the growth rate, the trees had been irrigated with nutrients and water for 15 years. Equal numbers of trees were selected from the irrigated site (I) and the control site (C) without irrigation. Descriptions for the two test groups are given in

Table 1.

Table 1. Characteristics of the test groups from Flakaliden. Average value (standard deviation in parentheses). Age of trees (Age), annual ring width (Rwidth), density at moisture content (MC) 12% (D12%), diameter at breast height with bark (dbh), diameter at 6 m height with bark, height of the tree (Height).

Test group. Average of five trees in each group	Age (years)	R_{width} (mm)	$D_{12\%}$ (kg/m^3)	dbh (mm)	d6h (mm)	Height (m)
Irrigated (I)	37	2.0 (0.2)	361 (21)	158 (13)	91 (13)	9.8 (0.6)
Control (C)	36	1.7 (0.1)	410 (14)	129 (10)	67 (5)	8.9 (0.3)

Stem discs 5 cm thick were cut 0.25 m and 5.25 m from the butt cut and stored in plastic bags and frozen until CT-scanned. The discs were used to determine age and growth-ring width. The logs were sawn through and through in north-south direction to 32-mm-thick boards and dried to 12% MC. Specimens for water sorption testing 200 mm long were cut 800 mm from the butt cut. In this investigation, specimens from the butt log, the two boards closest to the pith, were investigated. Before CT scanning, the test specimens were placed in a climate of standard conditioning at 65% relative humidity and a temperature of 22ºC (corresponding approximately to an equilibrium moisture content of 12%) for more than 2 months.

The specimens 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 in the 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 in room climate at a temperature of 23°–25°C during a period of seven days. After water sorption and drying, the test objects were oven dried at 103°C and CT scanned to achieve the dry reference images that were used in image processing.

2.2 CT scanning

A CT scanner consists of an X-ray tube and a detector array that rotate around the object being examined. After rotation, a large number of X-ray absorption coefficients are calculated. 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 normalized to the corresponding linear absorption coefficient for water, μ_{water}. This normalized value is referred to as the CT number (eq. (1)) (Herman 1980), where μ_x was the absorption coefficient for the tested material.

$$CT\ number = 1000 \times \frac{[\mu_x - \mu_{water}]}{\mu_{water}} \tag{1}$$

By assigning 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, at Luleå University of Technology was used for measurement. The CT images were obtained using scan settings of 110 kV, 50 mA and scan width of 10 mm. For image reconstruction, a standard Shepp-Logan algorithm was used. All images were stored as 512- x 512-pixel images.

2.3 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 dry. 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. (1992) and Lindgren (1991a, b).

The measurements were performed in the sapwood, heartwood and intermediate wood, mainly on the south side of the stem (to the left in the images, see Figure 1).

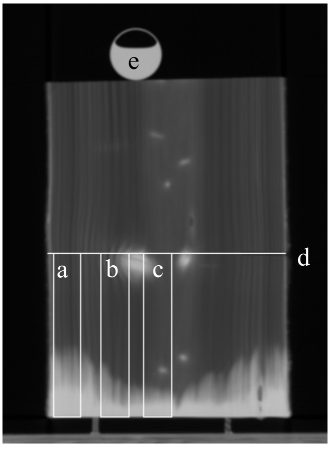


Figure 1. A vertical cross-section CT image showing sorption after 14 days in water; a, b and c show where the gradients have been measured in sapwood, intermediate wood and heartwood; d is a reference line 100 mm from the bottom surface, and e is a reference jar containing water.

When anomalies such as knots were present, the measurements were done on the north side of image. The measurements in the heartwood were close to the middle of the pith where heartwood was most likely to be found. The width of sapwood was measured from the stem discs and used for estimation of the border to the intermediate wood.

The intensity is proportional to the amount of water. White areas indicate increased water content. To ensure correct repositioning in the CT scanner, lasers were used to mark vertical reference points 100 mm from the bottom surface. A drill bit (3 mm) was used to make the holes on the north side of the test object.

The moisture content gradients were a mean value of the width of 15 mm and the scan thickness of 10 mm. The first 2 pixels (approximately 1.4 mm) close to the bottom edge were removed in order to exclude artifacts. A smoothing function was applied to the gradients based on the average of 11 pixels. The smoothing function smoothes the variation of the annual rings.

2.4 Multivariate analysis

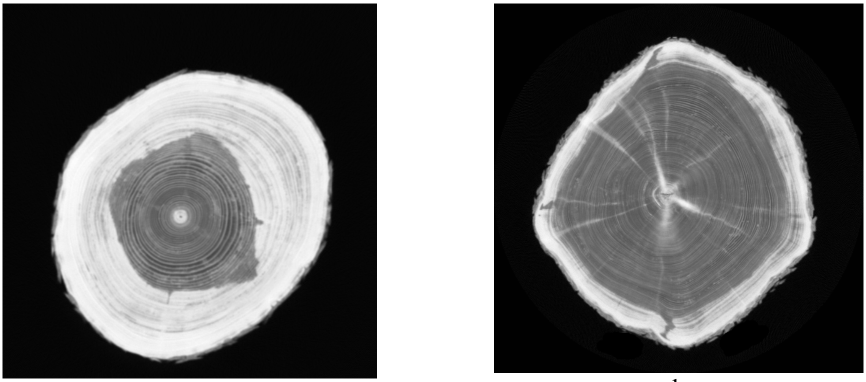
The MC gradients were analysed using a multivariate method with software from Umetrics, SIMCA P+10 (Umetrics AB 2004). The moisture content gradient was expressed as 95 variables (the number of millimetres measured), centred, but not scaled. These 95 measurements were used as X-variables in the multivariate analysis. The gradients were "filtered" for 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., summarizing and visualizing a dataset, multivariate classification and discriminant analysis and finding quantitative relationships among variables. The advantage of projection is that it applies to any shape of multivariate data, with many or few variables. It can handle missing, noisy, and highly collinear data.

Partial to least square structure (PLS) is a regression extension of PCA that is used to connect the information in two blocks of variables, X and Y, to each other. PLS-DA (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-DA is to find a model that separates classes of observations on the basis of their X-variables. 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. Q^2 is based on cross-validation (Eriksson et al. 2001). Small differences between R^2 and Q^2 indicate stable models that do not model noise. When analysing DmodX (distance to model) and score plot, a 95% confidence interval was used. To validate the models, observations from the work set were excluded before calibrating and were later used as a test set. Approximately 25% of the observations were randomly picked out to form 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 highest. The prediction falls to the class that has the highest predicted value.

3. Results and Discussion

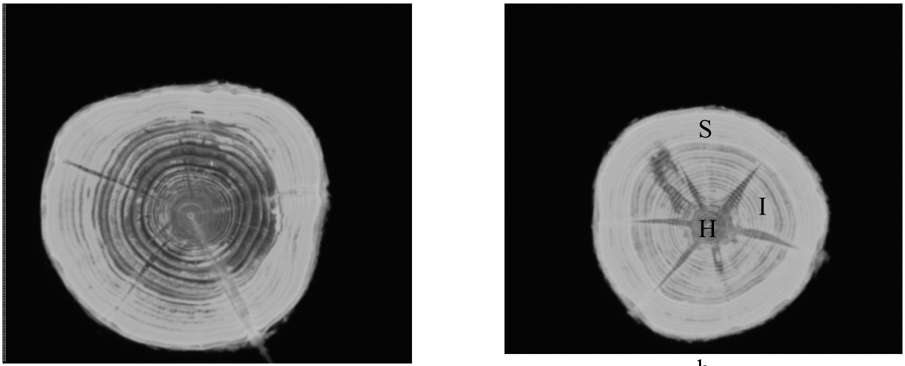
Figure 2 shows CT scans of green stem discs from earlier investigations (Sandberg 2002). In CT images, the greyscale is proportional to the green density; i.e., the amount of water also affects the greyscale value. In green spruce, MC in heartwood is approximately 30%–40% and in sapwood 110%–150% (Boutelje & Rydell 1989), and therefore the border between sapwood and heartwood is easy to detect and delimit.



a b

Figure 2. Cross-sectional CT images of green stem discs 250 mm from the butt cut. The intensity in greyscale is proportional to density. Heartwood appears as dark grey, and sapwood as white. a) = 64-year-old spruce with a breast height diameter of 110 mm; b) = 158-year-old spruce, breast height diameter 306 mm.

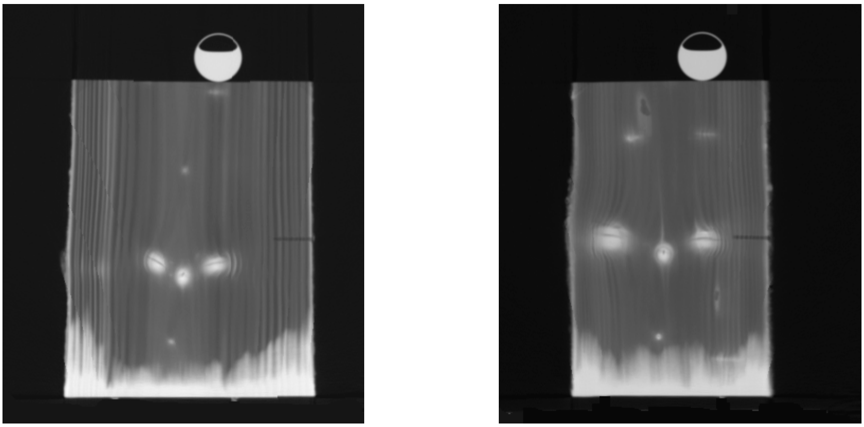
CT images of green stem discs of 37-year-old spruce show that density intensity between heartwood and sapwood is less obvious than it is in previous CT-scanned images (see Figure 3). The border between sapwood and heartwood is diffuse, and the greyscale value varies between the images, which show a variation in MC in green stem. There seems to be sapwood, heartwood and incompletely developed heartwood (intermediate wood) (see Figure 3b).



a b

Figure 3. Cross-sectional CT images of green stem discs 250 mm from the butt cut. a = 37-year-old tree irrigated with water and nutrients for 15 years; b = 36-year-old tree from the control group without irrigation. Heartwood (H), intermediate wood (I) and sapwood (S).

Figure 4 shows examples of vertical CT images after 14 days of water sorption in end grain corresponding to the stem discs in Figure 3. In Figure 4a, sapwood showed higher capillary water height (CWH) than heartwood/intermediate wood, but the border was unclear. Capillary water height is the distance water is absorbed longitudinally from the end of the board into the wood. In Figure 4b, the tendency to absorb water was similar in sapwood, heartwood and intermediate wood.



a b

Figure 4. Vertical CT images showing water absorption in end grain after 14 days, specimens corresponding to stem discs in Figure 3. White areas correspond to increased water content (density). On the top of the specimens there was a density reference filled with water. On the north side of the stem (to the right), reference holes were drilled 100 mm from the bottom surface. a) test object from irrigated site. The capillary water height was lower in the middle in the heartwood/intermediate wood area. b) test object from the control site. There was a small difference in water absorption visible within the radius of the trunk.

To investigate the CWH during water sorption within in the radius of the stem, MC gradients were measured in the three areas shown in Figure 1. Figure 5 shows typical MC gradients during 1, 3, 7 and 14 days of sorption measured in heartwood in the same test object. As shown in the figure, the moisture content close to the surface (MC_{surf}) increases from 100% after one day's absorption to 170% after 14 days' sorption. The sorption front moves longitudinally into the wood over time. The CWH when MC in heartwood was 20% ($CWH_{20\%}$) increased from 16 mm after one day to 36 mm after 14 days' absorption in heartwood.

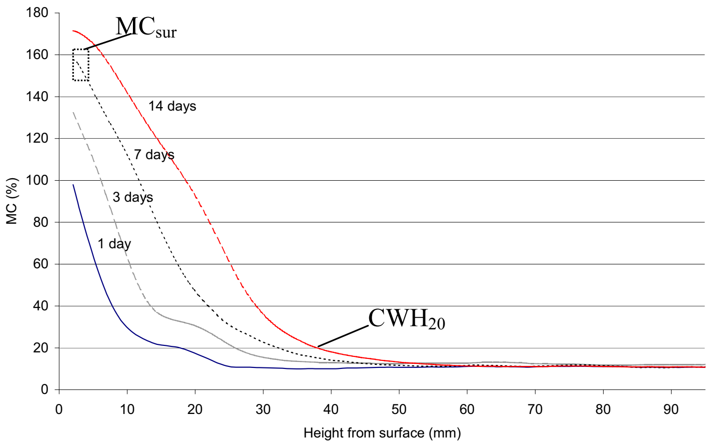


Figure 5. MC gradients measured in heartwood during absorption for 1, 3, 7, 14 days in end grain of spruce.

3.1 Sorption

3.1.1 Difference in the radius of the stem

PLS-D analysis was used to separate MC gradients according to location in the radius of the cross-section. Three classes were used: class 1 for sapwood (S), class 2 for heartwood (K) and class 3 for intermediate wood (M). The score plot in Figure 6 shows that all sapwood observations were separated to the right and that heartwood and intermediate wood were separated to the left after absorption for 14 days. The score plot is a summary of the relationships among observations. Similar observations are close to each other. Therefore the score plot indicates that MC gradients from heartwood and sapwood are quite dissimilar to each other and intermediate wood gradients are more like heartwood gradients. Heartwood observations, furthest to the left, had the lowest and steepest MC gradients, and sapwood observations, furthest to the right, showed a high CWH. Examples of MC gradients according to whether they belong to S, K or M are shown in Figure 7. The corresponding observations are marked A, B, C and D in the score plot in Figure 6.

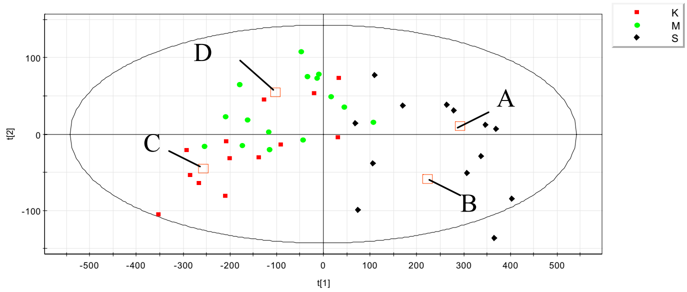


Figure 6. Score plot for MC gradients after 14 days' absorption in end grain. Observations from heartwood (K) and intermediate wood (M) are grouped to the left, and observations from sapwood (S) to the right. MC gradients corresponding to observations marked with rectangles (see Figure 7). Observations from sapwood are marked A and B, from heartwood C, and from intermediate wood D.

The gradient from heartwood, marked C, was steeper than the gradients from sapwood, marked A and B. The MC gradients from heartwood (C) and intermediate wood (D) had a $CWH_{20\%}$ approximately 30 mm from the surface, while the observations from sapwood have a $CWH_{20\%}$ between 47 and 55 mm from the surface. This can be interpreted as indicating that observations from heartwood and intermediate wood generally have a steeper gradient, with a lower MC and CWH, than observations from sapwood.

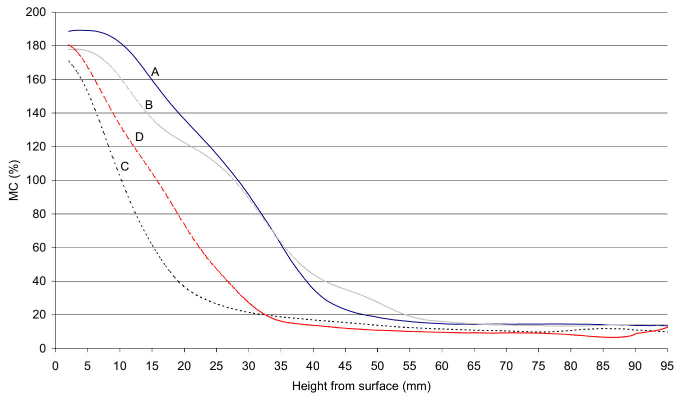


Figure 7. MC gradient in spruce after absorption for 14 days in end grain marked in Figure6. MC gradient from sapwood marked with A and B, heartwood with C, and intermediate wood with D.

Table 2 shows how well the models predict the observations in sapwood (S), heartwood (K) and intermediate wood (M). Sapwood was clearly different from heartwood and intermediate wood, while it was more difficult to separate heartwood from intermediate wood. During absorption for 1, 3, 7 days and 14 day, 71%, 71%, 78%, and 77% of the observations, respectively, in the work set were predicted correctly. In particular, sapwood observations were predicted correctly. For example, after absorption for 14 days, 14 of the observations from the work set and 3 from test set were predicted correctly as belonging to sapwood. Two observations, one from the work set and one from the test set, were predicted as intermediate wood. As seen in the score plot in Figure 6, some of the observations were found between the classes. In some cases, the capillary water height was higher close to the pith (probably juvenile wood) and was therefore predicted as intermediate wood. In other cases, some of the trees had almost no heartwood at all, as in Figure 3b, and the MC gradients were similar between sapwood and heartwood.

Table 2. Matrix showing how well the models predict the observations as belonging to sapwood (S), heartwood (K) and intermediate wood (M) during absorption for 14, 7, 3 days and 1 day. Observed and predicted from work set, observations from test set in parentheses.

Observed	Predicted			Model				
Absorption 14 days	S	K	M	Nr	PC	R^2X	R^2Y	Q^2
S	14 (3)	0 (0)	1 (1)	1	2	0.96	0.473	0.447
K	1 (0)	11 (3)	4 (1)					
M	1 (2)	4 (0)	11 (2)	77% predicted correctly				
Absorption 7 days	S	K	M	Nr	PC	R^2X	R^2Y	Q^2
S	12 (5)	1 (0)	2 (0)	2	3	0.967	0.527	0.472
K	0 (0)	12 (3)	3 (2)					
M	1 (1)	3 (2)	11 (2)	78% predicted correctly				
Absorption 3 days	S	K	M	Nr	PC	R^2X	R^2Y	Q^2
S	12 (4)	1 (0)	2 (0)	3	3	0.973	0.423	0.349
K	1 (0)	12 (2)	4 (1)					
M	2 (0)	4 (4)	10 (0)	71% predicted correctly				
Absorption 1 day	S	K	M	Nr	PC	R^2X	R^2Y	Q^2
S	14 (5)	1 (0)	0 (0)	4	2	0.931	0.394	0.341
K	2 (0)	10 (4)	3 (1)					
M	2 (2)	5 (1)	8 (2)	71% predicted correctly				

Apparently there was a difference in MC gradients in the radius of the stem, and the differences between heartwood, sapwood and intermediate wood increased with time. Generally, intermediate wood was more similar to heartwood than to sapwood.

3.1.2 Difference between irrigated group and control group

PLS-D analysis was used to separate MC gradients from the irrigated site (I) and the control site (C) after water sorption for 14 days in sapwood.

Table 3 shows how well the model predicts the observations into sites I and C after sorption for 14 days in sapwood. The matrix shows that 79% of the observations were predicted correctly, and MC gradients from I were clearly different from those from C in sapwood. The model indicates that the observations from the irrigated site in general had a higher MC level than the observations from the control site. However, there were few observations in the model, and the Q^2 value was rather low.

The trees from site I had been irrigated with water and nutrients during the last 15 years and should therefore only be detectable in the sapwood. This was verified by the fact there was no model separating differences in MC gradients from I and C in heartwood.

Table 3. Matrix showing how well the models predict the observations into irrigated site (I) and control site (C) after absorption for 14 days in sapwood.

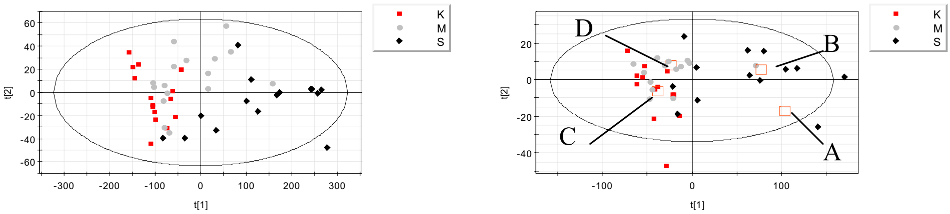
Observed	Predicted		Model				
Absorption 14 days	I	C	Nr	PC	R^2X	R^2Y	Q^2
I	9	1	5	2	0.923	0.414	0.244
C	3	6	79% predicted correctly				

3.2 Desorption

3.2.1 Difference in the radius of the stem

PLS-D analysis was used to separate MC gradients from sapwood (S), heartwood (K) and intermediate wood (M) during desorption. Figure 8a shows a score plot from modelling desorption for 3 days. Sapwood observations were more frequent to the right and heartwood and intermediate wood to the left. Furthest to the left, most of the heartwood observations correspond to an almost flat MC gradient, thereafter intermediate wood observations in the middle and sapwood, with the largest MC gradients, to the right.

After 4 days' drying, the observations have separated into two groups (Figure 8b). Observations to the left were almost dry (MC below 25%), and to the right in the score plot, eight observations have MC above 30%. MC gradients corresponding to the observations marked with rectangles in the score plot in Figure 8b are shown in Figure 9.



a b

Figure 8. Score plot after a, desorption for 3 days, and b, desorption for 4 days. MC gradients corresponding to observations marked in Figure 8b with rectangles are shown in Figure 9. Observations from sapwood are marked with A and B, from heartwood C, and D from intermediate wood.

The observations from heartwood (C) have an MC below 15%, while observations from sapwood marked A and B still have a moisture content above 40% close to the surface. It seems that sapwood observations reach a "dry" level below 20% MC more slowly than heartwood and intermediate wood (see Figure 9).

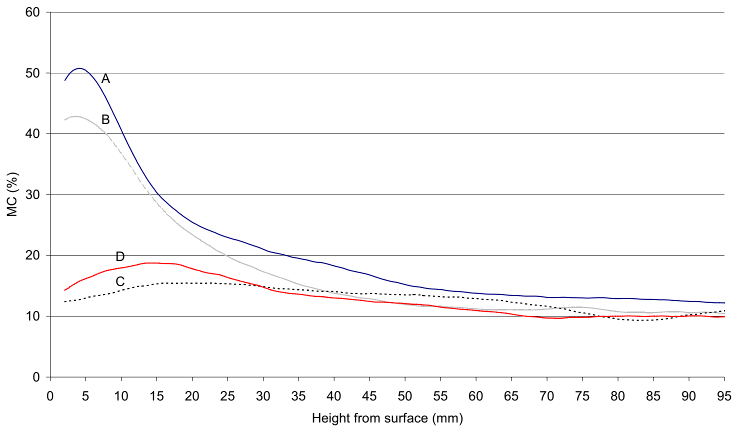


Figure 9. MC gradient after 4 days of drying from observations marked with rectangles in Figure 8b. Observations from sapwood marked with A and B, from heartwood with C, and from intermediate wood with D.

Table 4 is a matrix that shows how well the models predict the observations in sapwood (S), heartwood (K) and intermediate wood (M) after desorption for 4, 3 and 2 days. Differences between heartwood, sapwood and intermediate wood decreased with time and were most obvious after 2 days' desorption when 74% of the observations from the work set were predicted correctly. After 4 days of desorption, 70% were predicted correctly. When wood dries, the MC gradients level out and become "flat", and the differences between gradients become smaller and therefore more difficult to predict. MC gradients from sapwood were easiest to separate; for example, after 2 days of desorption, 12 observations from the work set and 5 from the test set were predicted correctly as sapwood. One MC gradient from the work set was predicted as heartwood and 2 MC gradients as intermediate wood. As seen in Figure 8, one observation from intermediate wood was among the sapwood observations.

Table 4. Matrix showing how well the models predict the observations into sapwood (S), heartwood (K) and intermediate wood (M) after drying for 4, 3 and 2 days. Observed and predicted from work set, observations from test set in parentheses.

Observed	Predicted			Model				
Desorption 4 days	S	K	M	Nr	PC	R^2X	R^2Y	Q^2
S	10 (3)	3 (0)	2 (2)	6	2	0.919	0.35	0.277
K	0 (1)	11 (3)	3 (2)					
M	1 (1)	4 (1)	10 (3)	70% predicted correctly				
Desorption 3 days	S	K	M	Nr	PC	R^2X	R^2Y	Q^2
S	12 (4)	2 (0)	1 (1)	7	2	0.96	0.368	0.328
K	0 (0)	12 (5)	3 (0)					
M	1 (0)	7 (2)	8 (2)	70% predicted correctly				
Desorption 2 days	S	K	M	Nr	PC	R^2X	R^2Y	Q^2
S	12 (5)	1 (0)	2 (0)	8	3	0.975	0.473	0.4
K	0 (0)	12 (5)	3 (0)					
M	1 (0)	5 (1)	10 (3)	74% predicted correctly				

3.2.2 Difference between irrigated and control group

Table 5 shows how well the models predict the observations into sites I and C after drying for two days, measured in sapwood and heartwood.

After desorption for two days, 85% of the observations in sapwood were predicted correctly. This means that MC gradients from irrigated wood have somewhat higher MC and CWH than the observations from the control site after desorption for 2 days in sapwood. After two more days of drying, the difference in MC gradients in sapwood between I and C seems to have vanished. In heartwood and intermediate wood, there was no difference between sites I and C after drying for two days (see Table 5).

Table 5. Matrix showing how well the models predict the observations into irrigated site (I) and control site (C) after desorption for 2 days. Observed and predicted from work set.

Observed	Predicted		Model				
Sapwood	I	C	Nr	PC	R^2X	R^2Y	Q^2
I	9	1	9	2	0.925	0.438	0.318
C	2	8	85% predicted correctly				

4. Conclusions

This investigation shows that MC gradients measured at three locations within the radius of the stem during sorption and desorption were different. In general, sapwood MC gradients had higher MC and capillary water height than observations from heartwood and intermediate wood. The behaviour of MC gradients from intermediate wood is more similar to that of MC gradients from heartwood than from sapwood.

There was an indication that there was a difference between MC gradients in sapwood from the fast-growing irrigated site and the control site after absorption for 14 days and during desorption for 2 days. The model indicates that the observations from the irrigated site generally showed a higher MC level than the observations from the control site.

The phenomena intermediate wood or a zone different in colour or/and moisture content distribution in green state from both heartwood and sapwood and situated between these zones have been observed both in soft and hardwood. (Chattaway 1952, Good et al 1955, Frey-Wyssling et al. 1959, Yazawa & Ishida 1965, Barnacle et al 1974). With some expectations moisture content of the intermediate wood is closer to the heartwood than sapwood. There are few observations but occurrence seems to be preferably in young trees.

The difference in density in CT images of fresh stem discs is due to the variation of water content, which indicates that heartwood has not developed and become uniformly dry with a lower green density than the sapwood. Most likely this is because heartwood in spruce starts to form close to the pith at an age about 20–30 years. In these relatively young spruces, sapwood has gradually started to convert into heartwood. Other investigations show that slow-growing, old trees, have a higher amount of extractives in the heartwood than fast-growing young spruce (Nylinder & Hägglund 1954). Heartwood percentage often increases in direct proportion to the age of the tree for many wood species (Hillis 1987). Wurz & Swoboda (1947) found that capillary water height was lower in 95-year-old spruce than in 20-year-old spruce. Frey-Wyssling & Bosshard (1959) show a gradual degradation of living ray cells with increasing distance from the cambium.

Since heartwood is so important factor for durability, and since the development of heartwood is a function of time, the age of the tree must be taken into account when durable timber is to be chosen for outdoor use. There is a risk that rapidly grown young spruce may be mixed with old, suppressed spruce with better properties for outdoor use. In young spruce the heartwood is very small but looking at the cross-section of the green stem the border between sapwood and intermediate might understood as heartwood.

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V

Liquid water absorption in Norway spruce measured with CT scanning and viewed as a percolation process

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Abstract

Liquid flow in wood is complicated to study, since wood is a nonhomogeneous, hygroscopic-porous, anisotropic material. However, such study is important, since many properties of wood are influenced by the presence of water. For example, during outdoor use, exposure to free water from dew, rain and condensation influences the durability of wood against fungi. The distribution of chemicals during impregnation and the ability to dry are other aspects dependent on the flow of liquid in wood. In this study, simulations of liquid water absorption in wood as a fibre network, percolation, have been compared with experimental water absorption in the longitudinal direction in spruce. With CT scanning, water distribution during liquid flow can be shown visually and measured by image processing. Liquid water absorption in end grain of spruce has been measured with CT scanning after 1, 3, 7 and 14 days liquid water absorption. The moisture content gradients have been measured in heartwood and sapwood. The simulations according to the percolation method show general agreement with the measured results.

Key words: *Norway spruce, Picea abies, capillary flow/liquid flow, CT scanning, percolation.*

Introduction

Wood cannot decay unless there is free water available in the wood cells (Zabel and Morrell 1992), and the most important condition for growth of blue-stain fungus is sporadic supply of bulk water (Kühne *et al.* 1970). Transport of liquids in wood also affects many other processes, such as impregnation, drying, surface treatment, *etc*. Therefore, models for liquid water uptake are important for many purposes. There have been many models in this field that have viewed the problem from different approaches, such as Stamm (1967), Kouali and Vergnaud (1991), Krabbenhoft and Damkilde (2004) and Virta *et al.* (2005). The problem is complex to model, since there are interactions between fluids, capillaries, size and shape of capillaries, displacement rate of air, viscosity of the fluids, wettability of the surfaces and pore size and distribution, and thus varying capillary forces. Modelling a fibre network, and thus the interaction between the capillaries and wood, as a nonhomogeneous material enables a more correct description of water transport in wood.

Computer tomography (CT) scanning is a nondestructive test method that makes it possible to study water absorption and drying over time. CT scanning has been used in many applications during the last 25 years, such as wood density and moisture content measurements (Lindgren 1985), artificial drying of wood (Wiberg 1995; Rosenkilde and Arfvidsson 1997; Danvind and Synnergren 2001) and measurement of water absorption (Sandberg 2006; Johansson *et al.* 2006).

In softwood it has been found that the primary pathway for axial flow is in longitudinal tracheids through bordered pit pairs (Wardrop & Davies 1961; Côté & Krahmer 1962; Richter & Sell 1992). In dry softwood nearly all the earlywood pits are aspirated, but a substantial number of the latewood pits remain unaspirated (Phillips 1933; Liese & Bauch 1967a; Petty 1972). This difference in behaviour of the pits is usually attributed to greater rigidity of the pit membranes and the greater cell-wall thickness found in latewood (Comstock and Côté 1968). The bordered pits are most frequently on the radial surfaces of the tracheids. The number of pits per tracheid varies from 50 to 300 in earlywood to fewer in latewood, and the pits are concentrated mostly on the radial surface (Stamm 1946). In spruce there are limited radial penetrations due to the relatively small proportion of ray tracheids, which are regarded as the main radial pathways (Liese and Bauch 1967b; Nyrén and Back 1960). The ray tracheids in spruce are also often interrupted by parenchyma cells at the junction of annual rings, which may explain why penetration often usually stops abruptly at a particular annual ring (Liese and Bauch 1967b).

The aim of this study of longitudinal water flow in end grain of spruce was to experimentally determine the moisture profile development and to compare it with theoretical profiles from a percolation simulation approach.

Materials and Methods

In this study, twenty Norway spruce (*Picea Abies* Karst L) were taken from a forest research site close to Vindeln in *Västerbotten*, Sweden. Half of the trees had grown with a good supply of ground water (wet) and half of them on a dry site (dry). The spruces from the dry site were grown 175 m above sea level, the spruces grown on the wet site 250 m above sea level. Different characteristics for the four test groups are shown in Table 1.

Table 1. Data for the test trees. Average of five trees in each group and standard deviation in parenthesis. Characteristics: age of trees (Age), annual ring width (R_{width}), density at moisture content (MC) 12% (Density12%), diameter at breast height with bark (dbh), height of the tree (Height)

Test group	Age (years)	R_{width} (mm)	$Density_{12\%}$ (kg/m^3)	dbh (mm)	Height (m)
Wet suppressed	67 (8)	1.5 (0.3)	414 (38)	191 (1.3)	18.3 (1.4)
Dry suppressed	137 (25)	0.6 (0.2)	491 (28)	179 (1.0)	14.3 (1.2)
Wet dominant	66 (2)	2.6 (0.2)	395 (30)	307 (0.8)	21.8 (2.1)
Dry dominant	158 (10)	1.0 (0.2)	452 (39)	289 (1.2)	22.2 (1.2)

The logs were sawn through and through in the north-south direction to 32-mm-thick boards and dried to 12 % MC. The drying was performed with 60 °C wet-bulb temperature and maximum dry-bulb temperature of 80 °C during the drying phase. The process was finished with steam conditioning at 90 °C. The total drying time was 84 hours. Specimens sawn through and through 200 mm long and 32 mm thick were taken 0.8 m from the butt cut.

Capillary water absorption was measured by CT scanning and image processing. Before CT scanning, the test specimens were placed in a climate of standard conditioning at 65 % relative humidity and a temperature of 22 ºC corresponding approximately to an equilibrium moisture content of 12 % for more than 2 months. Specimens were placed in a basin on bars of stainless steel in 5-mm-deep tap water for end-grain absorption. The measurements were carried out in a 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 absorption. Reference points with a diameter of 3 mm were used to ensure correct repositioning in the CT scanner between measurements.

CT scanning and image processing

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 x 512 pixels. 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 and not moisture content. Two density measurements must be made in order to evaluate moisture content, one with the 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 dry.

Since wood swells during absorption, 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 difference in CT number in each pixel is then due to presence of water. 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 x 7 pixel area (approximately 3 x 3 mm) can be expected according to Lindgren. The CT image in Figure 1 shows absorption after 14 days in water. The measurements were performed in the sapwood and heartwood, mainly on the south side of the stem, to the left in the images (Figure 1). The MC gradients were measured as a volume element, W×t×(hxn) in Figure 1, where W_s and W_h are the width of sapwood and heartwood. t is the scan thickness, 10 mm in the middle of the test specimen, and h is the height of the pixel, ca 0.7 mm, number of pixels and n is number of pixels vertically. The MC gradient is a mean value of the volume element W×t×h in each position from h1 up to the reference point 100 mm from the end-grain surface.

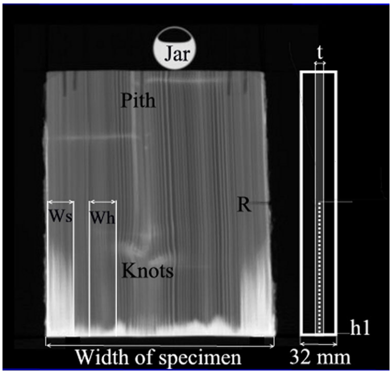

Fig 1. CT image of a vertical cross-section showing absorption after 14 days in water. Ws and Wh show where the gradients are measured in sapwood and heartwood. The gradients in heartwood are measured 12 mm from the sapwood borderline. R is a reference point 100 mm from the end-grain surface. On the top is a jar containing water as a density reference. t = 10 mm is the scan thickness, and h is the height of the pixel. h1 is the first pixel in the MC gradient up to 100 mm from the end-grain surface

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. To ensure that the measurements were done at the same position, reference marks were used. The first two pixels (approx. 1.4 mm) close to the bottom edge were removed from the MC gradient in order to eliminate artifacts.

Fibre level modelling using a percolation approach

A model describing absorption of water in the capillary network formed by the fibres in wood has been developed and adapted to absorption in the longitudinal direction in softwood (Salin 2008). The driving force in that model is the capillary suction created by the meniscus in the fibre lumen. This causes a flow of water into that lumen from adjacent fibres through tiny openings (bordered pits). It is assumed that all flow resistance is concentrated to these openings. The lumen diameter—and thus the capillary suction—is a stochastic variable in the model, and the average diameter also varies across the annual ring. A pressure field is thus created in the water phase, from the lumens being filled to the water reservoir from which the absorption into the wood piece takes place. Calculation of this pressure field—as a discretised Laplace equation—is a time-consuming part in the model. Together with the pressure field, the water flow into and out from each fibre involved is obtained. When a fibre has been fully filled with water, the flow continues into the neighbouring fibres through the tiny openings, and a new pressure field calculation has to be performed. In this way, the absorption simulation proceeds fibre by fibre.

An important factor that influences the calculated absorption process is the number of openings between fibres. In dried softwood, the majority of the openings—bordered pits—are aspirated, *i.e.*, are closed. This means that there are limitations regarding the amount of flow paths available for water penetration into the wood. In the model, it has been assumed that each fibre has 100 bordered pits and that these are aspirated with the probability p. Stochasticity in this respect also is thus included in the model. Values for p in the range 95%–98.5 % have been studied.

For p = 96%, *i.e.*, an open structure, almost all fibres (~97%) are eventually filled with water. For p = 98.5 %, *i.e.*, a closed structure, all flow paths will eventually reach a dead end, and the absorption will stop. It is well known from general percolation theory that there is an exact p value below which continuous paths in a very large network always exist and above which no such paths exist (Stauffer and Aharony 1992). It is of course not the aspiration rate alone or the total number of openings that determines how open the structure is, but their combination.

Results

MC gradients

The MC gradients show the highest moisture content a few millimetres into the wood as the water moves longitudinally into the specimens. Then moisture content decreases with height from end-grain surface and eventually levels out to approximately 12 %. Average MC gradients from the test group in Table 1 are shown for 1, 3, 7 and 14 days of capillary absorption of water in sapwood (Figure 2) and heartwood (Figure 3).

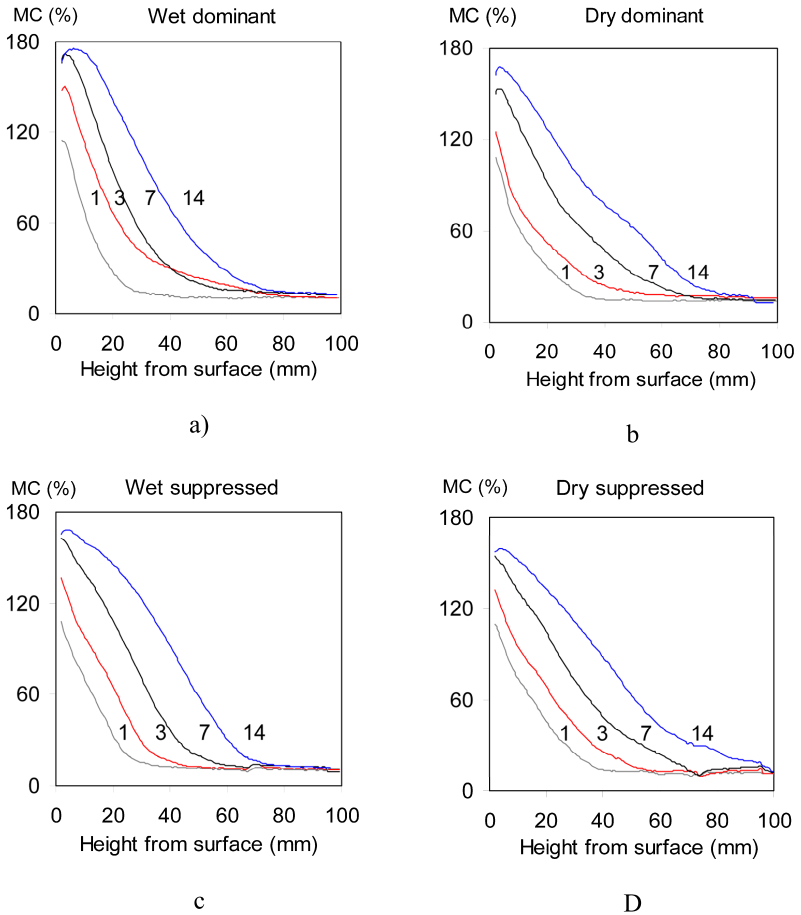

Fig 2 Average of five MC gradients from the test group in Table 1 measured in sapwood after capillary absorption for 1, 3, 7 and 14 days. Measurements were made 0.8 m from butt cut

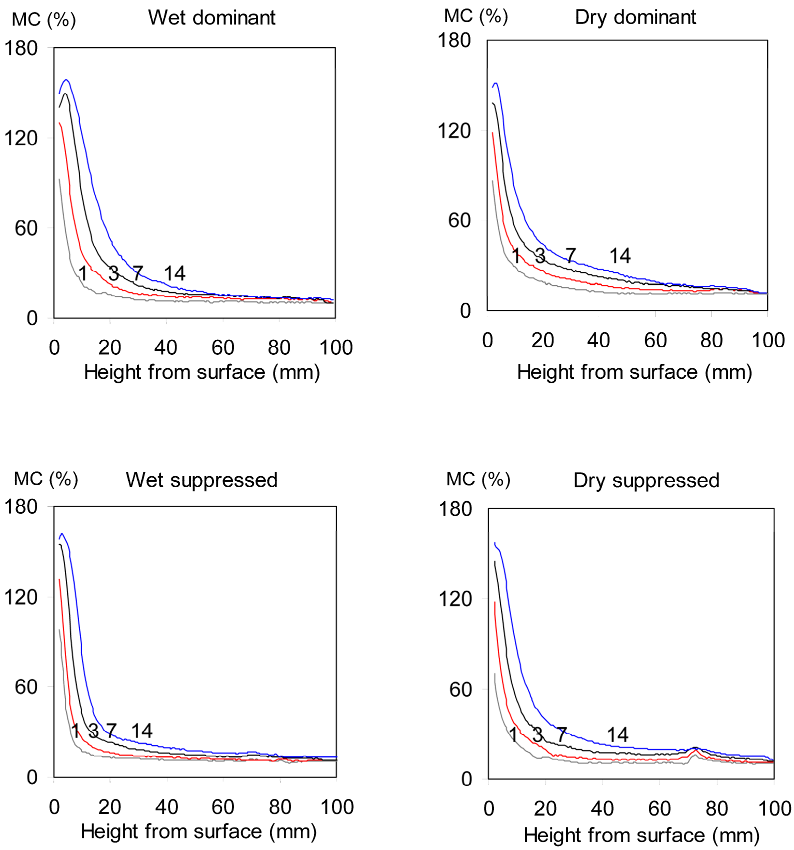

Fig 3 Average MC gradients from the test group in Table 1 measured in heartwood after capillary absorption for 1, 3, 7 and 14 days. Measurements were made 0.8 m from butt cut

In Figures 2 and 3, the average MC gradients show an even increase in absorption from day 1 to 14 days.

Absorption rate

From the MC gradients in Figures 2 and 3, the surface area under respective MC gradient was calculated, corresponding to absorbed volume of water, and plotted as a function of the square root of time. This gives approximately straight lines from the regression lines (see Figure 4 and Figure 5).

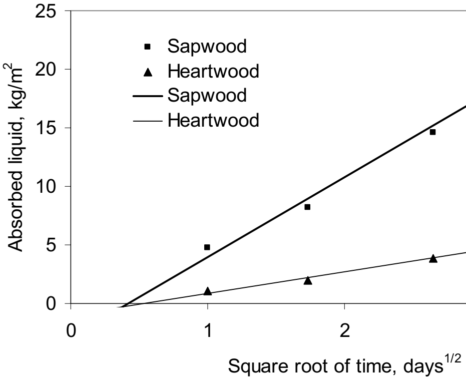

Fig 4 Absorption rate for test group wet suppressed of spruce. Absorption is expressed per area of wood with about 12 % MC

Figure 4 presents typical absorption rate results for sapwood and heartwood. A clear difference between sapwood and heartwood can be seen. The experimental points are located close to straight lines with square root of time as independent variable. The regression lines do not go through the zero point, giving an impression of a time lag. In Figure 5, the corresponding regression lines are forced to go through the zero point in order to make it easier to compare the different test groups. It is interesting to note that for both sapwood (with one exception) and heartwood, the slope of the lines in Figure 5 increases with increasing density. In addition to this density dependency ($R^2 = 0.82$ for sapwood and 0.96 for heartwood), there seems to be no other difference between the test groups. This indicates that the growth site has no direct significant influence, only the wood density—which of course in turn may be growth-site dependent.

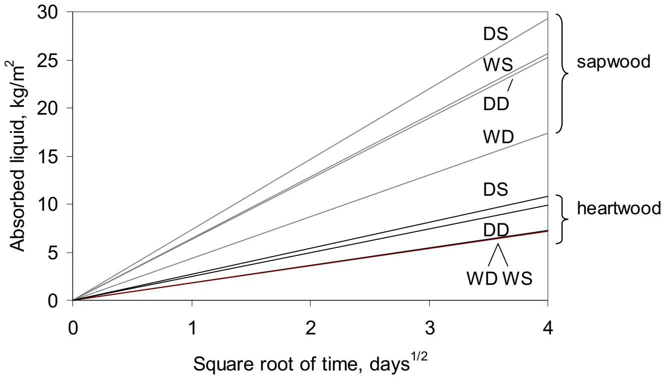

Fig 5 Absorption rate for different test groups of spruce. Absorption is expressed per area of wood with about 12% MC. Test groups in Table 1, DO (dry suppressed), DD (dry dominant), WS (wet suppressed), WD (wet dominant)

Fibre level simulations

Figure 6 shows simulations according to the method described above with its simplified assumptions. The curves are an average of several simulations. The horizontal axis shows the total fibre length.

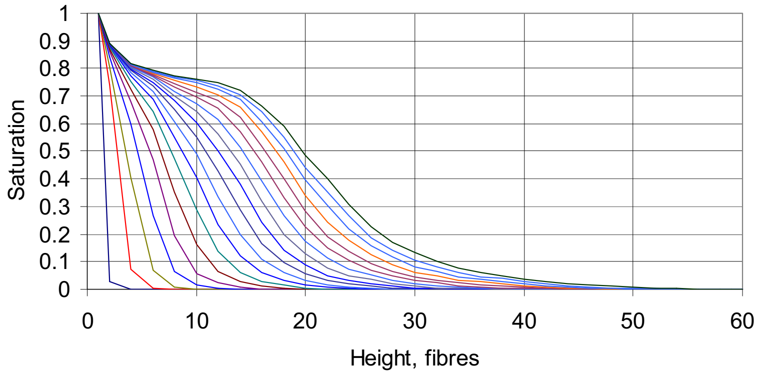

Fig 6 Simulation with percolation method. Each curve is the average of several simulations on a 30 x 30 x 60 network (Radial x Tangential x Longitudinal). The curves are equidistant in the sense that equally many fibres are filled between adjacent curves. ”Height, fibres” refers to a virtual height composed of approximately 3-mm-long, slightly overlapping vertical fibres.

Figure 6 illustrates a calculation for p = 97.5 %, and almost all fibres are eventually filled with water. The lowest horizontal fibre layer is totally filled with water as assumed, but further up the saturation drops, as some fibres are not reached by any flow paths. Rather rapidly, an equilibrium saturation is reached, *i.e.*, new paths are found with the same rate as old ones are blocked. This equilibrium is seen as a horizontal plateau at about 75 %–80 % saturation. This level in the graph is thus an indirect measure of the openness of the fibre structure.

Discussion

In this study, we have not been interested in what is happening close to the sample end, but rather what happens generally in absorption in spruce. The fibre structure in the sample end is probably damaged due to machining during sample preparation. The measurements with CT scanning show a low MC close to surface that can be due to artefacts because of big differences in density, state of inertia, degree of wetting or air in the wood structure close to the surfaces. This has not been investigated, and therefore measurements 1.4 mm from surfaces into the wood have been removed from the data.

There is a clear difference between the moisture profiles in sapwood and heartwood, as expected (see Figures 2 and 3). Figures 2 and 3 represent average profiles for 5 samples within each test group. Variations between the MC gradients in the form of MC level and height of the propagation front occur depending on the wood properties such as degree of aspiration, heartwood and sapwood, latewood, earlywood, *etc*. No distinct difference is seen in the average profiles between test groups for either for sapwood or heartwood.

The measurements show that the MC gradients increase with time in a uniform way, and the absorbed amount of water can be expressed as a linear function of the square root of time. This is illustrated in Figure 4 for the FU sapwood and heartwood test groups. The corresponding regression lines for all test groups are given in Figure 5. It should be noted that straight lines are obtained for heartwood also, indicating that the absorption process continues for a long time, but at a low rate.

Comparison of measurements with simulation

As illustrated by Figure 6, there is an upper limit for the saturation (except for the volume close to the sample end). Such a plateau is not seen for the experimental moisture profiles. One obvious reason is that 14 days is a too short experimental time. The first curves of Figure 6 are, however, in relatively good agreement with experimental sapwood curves, especially if it is assumed that the plateau level is close to full saturation. It should be noticed that the highest MC-values seen in Fig. 2, do not reach higher than to 160-175 % MC, which does not correspond to full saturation. Based on an assumed cell wall density of 1500 kg/m^3 and sample densities as given in Table 1, these MC-values correspond to a saturation in the range 0.76 – 0.92. This may thus be an indication of a plateau, although not clearly seen. For heartwood, the existence of a plateau and its saturation level are clearly an open question. The openness of the capillary fibre structure in dried spruce can thus not be determined quantitatively.

When the equilibrium saturation level is reached in the absorption process with an open structure, *i.e.*, for p values below the percolation threshold, the flow path structure remains, on average, constantly upwards. This means that the flow resistance is proportional to the vertical length in the sample, *i.e.*, proportional to the amount of water absorbed. As the suction pressure in fibres being filled is, on average, constant, the pressure gradient in the water phase will be inversely proportional to the height, *i.e.*, to the amount of water absorbed. Together, these two dependencies will thus result in an absorbed amount of water proportional to the square root of time, except for a short initial phase. This theoretical result is in good agreement with the results seen in Figures 4 and 5. It should be mentioned that for a pure diffusion process into a semi-infinite solid, the total uptake is also proportional to the square root of time. In this sense, absorption is similar to a diffusion process—except for the initial phase. It should, however, be noted that only a part of the fibres are filled—corresponding to the maximum saturation.

In the percolation model, a constant aspiration rate and a constant bordered pit flow resistance is assumed across the annual ring, *i.e.*, no difference between earlywood and latewood in this respect. Such differences could easily be introduced into the model in further studies to give better fit with experimental results. As preparation of a diagram like Figure 6 requires several weeks of computational time on an ordinary PC, such studies have not been performed at this stage.

Conclusions

Investigation of longitudinal absorption in spruce using the CT-scanning technique has been found to be a powerful method. Further studies should, however, preferably be extended over longer absorption times than the 14 days of this study.

Comparison of results from the percolation model with experimental data show promising similarities that suggest further development of such models. It is thus proposed that model parameters should be adapted in a more systematic way to find a good fit with experimental data. As a result, a better understanding of the capillary network properties in spruce would be obtained.

Acknowledgements

We would like to thank Norrskogs Forskningsstiftelse — NFS, the Swedish Agency for Innovation Systems — VINNOVA, the Swedish Forest Industries Federation — Skogsindustrierna and the Swedish Council for Environment, Agricultural Sciences and Spatial Planning — FORMAS for supporting this work. Thanks to Vindeln´s Experimental Forest for helping select the trees and for help with the field work.

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ORIGINAL ARTICLE

Degradation of Norway spruce (*Picea abies*) heartwood and sapwood during 5.5 years' above-ground exposure

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Abstract

Differences in durability between heartwood and sapwood of Norway spruce [*Picea abies* (L.) Karst.] were investigated to determine wood qualities most favourable for use in outdoor constructions above ground. Trees grown on sites with either good or poor access to water were used. Seventy-eight specimens measuring $20 \times 50 \times 300$ mm^3 separated into heartwood and sapwood, half untreated, half painted, were exposed horizontally outdoors above ground for 5.5 years with the pith side up and the bark side down. Crack length and crack number were measured. Fungus growth and surface changes were visually estimated. Fungus type was determined by microscopic analysis. The main finding was that spruce heartwood had fewer and shorter cracks and less surface-discolouring fungus growth than sapwood. This was valid for both painted and untreated wood. After 2 years' exposure, the cracks in sapwood (upper surface) were more than three times longer and about five times more numerous than in heartwood for both painted and untreated boards. Microscopic study showed that surface discoloration was due mainly to *Aureobasidium pullulans*, together with a few other discolouring fungi. After 5.5 years, initial decay was established on the surface and in the end grain of four untreated test objects.

Keywords: *Cracks, decay, heartwood, outdoor exposure, Picea abies Karst., sapwood, spruce.*

Introduction

Wood surfaces exposed outdoors above ground undergo degradation caused by such influences from the environment as sunlight (visible and infrared radiation), moisture (dew, rain, snow), temperature, oxygen and atmospheric pollutants (Hon, 1983).

Degradation of wood surfaces exposed to weather has been studied by a number of researchers from different points of view on different species; for example, the influence of ultraviolet radiation and colour changes (Browne & Simonson, 1957; Morgan & Orsler, 1968; Hon & Ifju, 1978; Hon et al., 1980; Arnold et al., 1992), checks and anatomical changes examined by microscopy (Miniutti, 1967, 1973; Sell & Wälchli, 1969; Sell & Leukens, 1971; Borgin et al., 1975; Sandberg, 1999; Sandberg & Söderström, 2006), surface treatment (Zicherman & Thomas, 1972; Ashton, 1979; Feist, 1982*b*; Derbyshire & Miller, 1997), biological degradation (Arndt & Willeiter, 1969; Kühne et al., 1970; Bergström et al., 2005) and accelerated weathering (Feist & Mraz, 1978; Blom & Bergström, 2005).

Degradation of wood during outdoor exposure is a complex combination of biotic, chemical and physical agents acting alone or in combination and here divided into the categories of weathering and decay.

Weathering is a surface degradation that has little effect on strength properties and is caused primarily by photochemical damage, oxidation of breakdown products, leaching of soluble decomposition products, hydrolysis, mechanical damage from shrinkage and swelling and discoloration by blue-staining fungi. In decay, or biological destruction, microorganisms participate, the whole thickness of the wood can be affected and strength can be reduced considerably. Weathering is a slow process compared to decay, which can destroy wood in just a few years if conditions are favourable to the fungi. For instance, fungi need free water available in the wood cells

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(Feist, 1982*a*; Zabel & Morrell, 1992; Rowell, 2005).

Unprotected wood surfaces exposed to weather undergo changes in colour and structure. The surfaces become rough and develop cracks, latewood grain rises above earlywood, the surface erodes, and the cracks increase in size and number as long as degradation of the surfaces continues. After some time, a thin silver–grey layer, 0.08–0.2 mm thick (Browne, 1960), arises when rain leaches products of decomposed lignin and leaves the fibres of cellulose. Greying on wood in the presence of moisture is practically always due to growth of blue-staining fungi such as *Aureobasidium pullulans* on the surface of the wood (Sell, 1968; Sell & Wälchi, 1969; Kühne et al., 1970; Sell & Leukens, 1971). Without blue-staining fungi, the surface becomes more white than grey (Sell & Wälchli, 1969). The presence of water accelerates the weathering process by causing splitting and cracking, since the wetting and drying cause stresses in the wood when wood swells and shrinks (Rowell, 2005; Feist, 1982*a*).

Different fungi need different conditions in terms of nutrients, temperature and moisture in order to establish themselves on wood and survive, and extant fungi may determine the subsequent succession of fungi that colonizes the wood. Both the chemical composition and the specific morphology of any wood species influence the rate of decay by particular decay fungi (Findlay, 1965; Scheffer & Cowling, 1966; Scheffer, 1973). The growth of fungi can decrease and even stop if some of the conditions for growth are limited (Scheffer, 1973).

Hirmke et al. (1998) investigated resistance to rot fungi according to the European standard EN 113 (2004) and found no difference between heartwood and sapwood of spruce. In contrast, a longer average life for spruce heartwood than sapwood in ground contact was found by Bergman and Mazur (1982). The present author found a difference in degree of discoloration between heartwood and sapwood was found after 1.5 years of exposure (Sandberg, 2004). Similar results were found with accelerated testing with a Mycologg by Blom and Bergström (2005). Frühwald et al. (2007) found more fungal growth, registered by digital photography and evaluated by image analysis, on spruce sapwood than on heartwood.

An overview of testing and evaluation of natural durability in above-ground conditions reveals how complex and difficult it is to evaluate durability and compare different tests with each other (Råberg et al., 2005). A test with water sorption in end grain showed that the capillary water height was three to four times higher in sapwood than heartwood in spruce studied with computed tomographic (CT) scanning and image analysis (Sandberg, 2002). Based on these results, this study was planned on the hypothesis that there is a difference between heartwood and sapwood of spruce (*Picea abies*) during above-ground exposure, since less sorption of water leads to faster drying and thus a shorter wetting time, less favourable living conditions for fungi and less moisture-related movement in the wood. The purpose of this work was to study heartwood and sapwood of spruce during weathering, with the aim of finding wood with qualities suitable for outdoor use above ground. Criteria important for the wood user have been studied with regard to microbiological activity and cracking. Visual evaluation was used to study the number and length of cracks, as well as surface change and discoloration.

Materials and methods

Materials

The trees used in this experiment were chosen to provide large differences in the parameters that can influence water distribution in the tree, such as the size of the crown, wood density and availability of water. Twenty trees of Norway spruce [*Picea abies* (L.) Karst.], half of them suppressed (Su) and half of them dominant (Do), were taken from two sites. One site, moist forest, had a good supply of water (wet), and the other site, sandy heath, was without free ground water (dry). Thus, the trees could be placed into four groups with five trees in each: wet suppressed, dry suppressed, wet dominant, dry dominant. Characteristics for the four test groups are shown in Table I. Several characteristics were measured: age of the trees (Age), annual ring width ($Ring_{width}$), density at moisture content (MC) 12% ($Density_{12\%}$), diameter at breast height (dbh) and height of tree (Height).

The trees were taken from a forest research site close to Vindeln in north-east Sweden (64°13′ N, 19°41′ E). The spruces from the dry site were grown 175 m above sea level. The spruces grown on the wet site grew 250 m above sea level. The trees were cut into 5 m logs. The logs were sawn through and through in the north–south direction into boards 32 mm thick and dried to 12% MC. Drying was performed with 60°C wet-bulb temperature and maximum dry-bulb temperature of 80°C during the drying phase. The process was finished with steam conditioning at 90°C. The total drying time was 84 h. Test specimens were taken 1.2 and 1.5 m from the butt cuts of the logs. The heartwood specimens were taken from west 1 and east 1 (Figure 1), avoiding the pith. The sapwood panels

Table I. Data for the test trees.

Test group	Age (years)	$Ring_{width}$ (mm)	$Density_{12\%}$ (kg m^{-3})	dbh (mm)	Height (m)
Wet suppressed	67 ± 8	1.5 ± 0.3	414 ± 38	191 ± 1.3	18.3 ± 1.4
Dry suppressed	137 ± 25	0.6 ± 0.2	491 ± 28	179 ± 1.0	14.3 ± 1.2
Wet dominant	66 ± 2	2.6 ± 0.2	395 ± 30	307 ± 0.8	21.8 ± 2.1
Dry dominant	158 ± 10	1.0 ± 0.2	452 ± 39	289 ± 1.2	22.2 ± 1.2

Note: data are shown as the mean value for each group ± SD.
dbh = diameter at breast height.

were taken as close as possible to the bark in the west or east direction. The specimens separated into heartwood and sapwood was planed to dimensions of 20 × 50 × 300 mm^3.

Half of the test specimens were painted with white acrylic latex paint, 180 g m^{-2}, corresponding to a coating 60 μm thick. No primer coat was used. The same treatment was used to seal the end grain. The unexposed lower surfaces of the specimens were left untreated. Paint with somewhat unfavourable moisture dynamics when used without a primer coat was chosen as it can speed up the degradation and decay process. The specimens were placed in a climate of standard conditioning, relative humidity 65% and temperature 22°C, corresponding to approximately 12% MC before painting and after painting until equilibrium. The test included 78 specimens, 20 untreated heartwood, 20 painted heartwood, 19 untreated sapwood and 19 painted sapwood, with five pieces of wood from the four test groups in Table I except from dry suppressed, which had four. (It was not possible to take specimens from the sapwood of one particular suppressed tree owing to the narrowness of the sapwood.)

Methods

On 16 May 2002, the specimens were placed outdoors in Skellefteå, Sweden (64°45′ N, 20°56′ E), in a horizontal position 1 m above ground, with the tangential pith side upwards (Figure 2) resting on four screw heads with a distance of 5 mm to the support to avoid surface contamination. The test specimens were fastened with a string to avoid cracks arising from fastening. Horizontal exposure was chosen to leave water and snow on the surface and expose the cross-section of the specimens.

The specimens were exposed outdoors for 5.5 years. During that time, the test pieces were inspected 13 times, usually in May and October. Temperature, precipitation and weight changes related to start weight at 12% MC on 16 May 2002 were recorded from 2002. The following parameters were measured: crack length, number of cracks on upper and lower surfaces, visual estimation of the growth of fungus on the lower surface and visual appearance on upper surfaces and end grain. The upper surfaces (50 × 300 mm^2) and lower surfaces (50 × 300 mm^2) of the specimens were examined. Microscopic analyses to determine fungi were done twice, once in 2005 and again in 2007. Inspection and visual evaluation were performed after 3–5 days of dry weather so that the wood surfaces were dry. The surfaces were not cleaned before examination. The specimens were weighed and examined in a conditioned room and then set out within the same day.

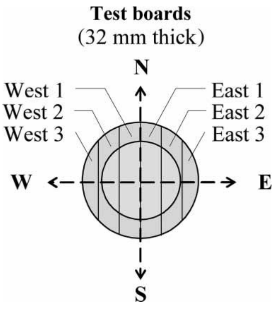

Figure 1. Sampling strategy of specimen and sawing pattern of the logs.

Cracks

A steel ruler, a thickness gauge and a loupe were used to determine number and length of cracks on the upper and lower surfaces of the specimens. Cracks with a maximum width less than 0.2 mm and cracks in knots were not counted. If two cracks coincided, they were counted as one. Numbers of cracks are the total sum of cracks on the 50 × 300 mm^2 surfaces of each specimen. Crack length

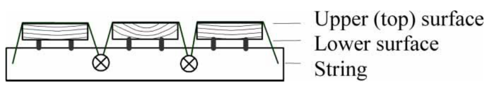

Figure 2. The test objects lying on four screw heads with a distance of 5 mm to the support, fastened with a string.

is the total length of cracks on the $50 \times 300\ mm^2$ surfaces of each specimen.

Crack length is not normally distributed, especially during the first years of exposure, since some of the samples have no cracks at all. To compare the mean crack lengths with statistical methods, data were transformed before analysis by log(1 + data), and thereby normal distribution was approximately fulfilled. Analysis of variance (Welch approximation) and mean comparison with Tukey–Kramer HSD was then applied to the transformed data at 5% significance level. In the statistical test, the p values were very small, which means that the differences can still be considered significant, although the assumption of normal distribution was approximately fulfilled.

Visual evaluation and microscopic analysis

Discoloration due to fungus growth on the lower surfaces and weathering changes to the upper surfaces were estimated by visual evaluation. The test pieces were placed in a falling order, ranked into groups, according to criteria for the visual inspections (Table II). Photographs were then taken.

Visual changes on upper surfaces

Visual changes on the upper surfaces and end grain were studied on painted and untreated specimens, evaluated according to the criteria in Table II. Cracks with a width between 0.2 and 0.4 mm were considered small, cracks with a width between 0.4 and 0.8 mm were considered medium, and cracks wider than 0.8 mm were considered large.

Discoloration of lower surfaces

Discoloration was estimated visually on the lower surfaces of both untreated and painted specimens. As can be seen in Figure 9, there were differences in the discoloration of the wood depending on whether the upper surfaces were untreated or painted; therefore, these categories are taken up separately in Table II.

Microscopic analysis

Small samples for microscopic analysis were cut with a wood chisel after investigations with a loupe so that different kinds of growths could be detected. In 2005, 14 test objects were analysed under the microscope. In 2007, the lower surfaces of all untreated specimens, as well as five upper surfaces and five end grains from untreated specimens, were analysed under a microscope by T. Nilsson (Agricultural Science, Uppsala, Sweden).

Results

Cracks

Number of cracks on upper surface. Figure 3 shows that cracks were visible on upper surfaces of untreated specimens after 6 months of exposure. After 1 year's exposure, cracks were also visible on painted sapwood

Table II. Definition of degree of discoloration and visual changes of the test specimen.

Rating	Criterion			
Group	Discoloration lower surface, untreated top surface	Discoloration lower surface, painted top surface	Visual changes, unpainted top surface and end grain	Visual changes, painted top surface and end grain
0. No influence	No trace of discoloration or decay	No trace of discoloration or decay	No trace of cracks or damage	No trace of cracks or damage
1. Slightly affected	Yellow to light grey surface with small dark spots	Yellow to light grey surface with small dark spots	Light grey surface with no or few superficial cracks	White intact coating with no or one superficial crack
2. Distinct effect	Light grey surface with grey discolorations in groups and streaks	Yellow to light grey surface with grey discolorations in groups and streaks	Light grey surface, small and medium cracks, generally at end grain	Surface with small and medium cracks, generally at end grain
3. Large effect	Grey surface with large areas with dark grey to black discoloration	Yellow to grey surface with large areas with dark grey discoloration	Light grey surface with small, medium and large cracks; end-grain cracks, some through surfaces	Surface with small, medium and large cracks; end-grain cracks some through, paint loss along annual rings

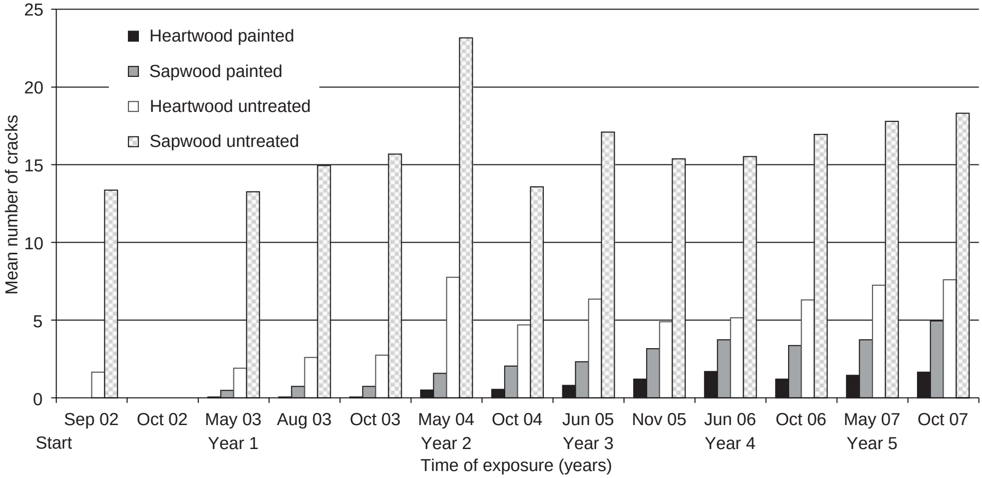

Figure 3. Mean number of cracks on the 50 × 300 mm upper surface of spruce specimens from 2002 to 2007.

and after 1–2 years on painted heartwood. Painted heartwood had the fewest cracks and untreated sapwood the most. After 2–2.5 years' exposure, cracks started to coincide, especially in the sapwood, and some of the end-grain cracks penetrated through both surfaces. No measurable cracks were found on one measurement occasion, October 2002.

Crack length, upper surface. Mean total crack length for sapwood and heartwood, untreated and painted, is shown in Figure 4. After 2 years of exposure, the cracks in sapwood were about three to four times longer on average than those in heartwood for both painted and unpainted specimens.

There was a significant difference in average crack length between sapwood and heartwood for painted specimens 2004–2007 and unpainted test objects 2003–2007.

Crack length, lower surface. Figure 5 shows the crack lengths on the lower surfaces. Compared to the upper surfaces (Figure 4) there are more cracks on the lower surfaces of specimens with painted upper surfaces for both heartwood and sapwood, and fewer cracks on untreated specimens. There was a sig-

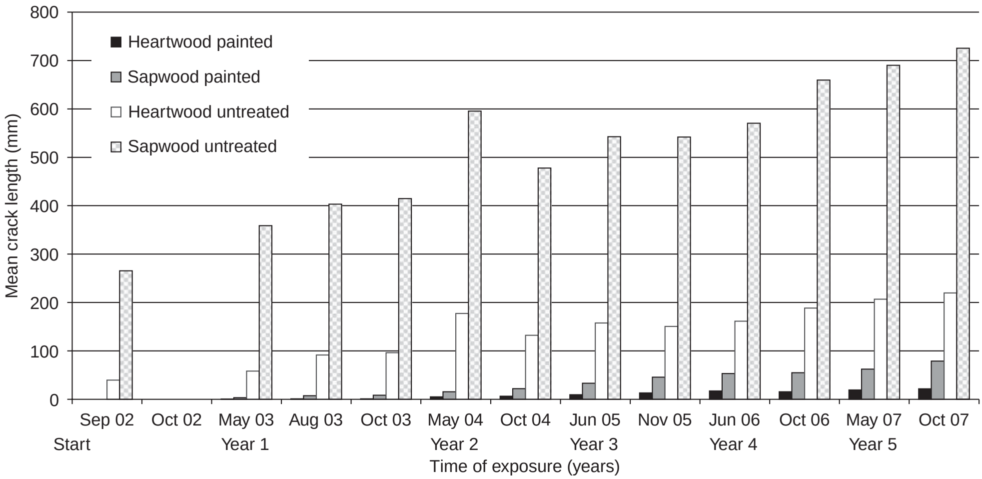

Figure 4. Mean crack length on the 50 × 300 mm upper surface of spruce specimens from 2002 to 2007.

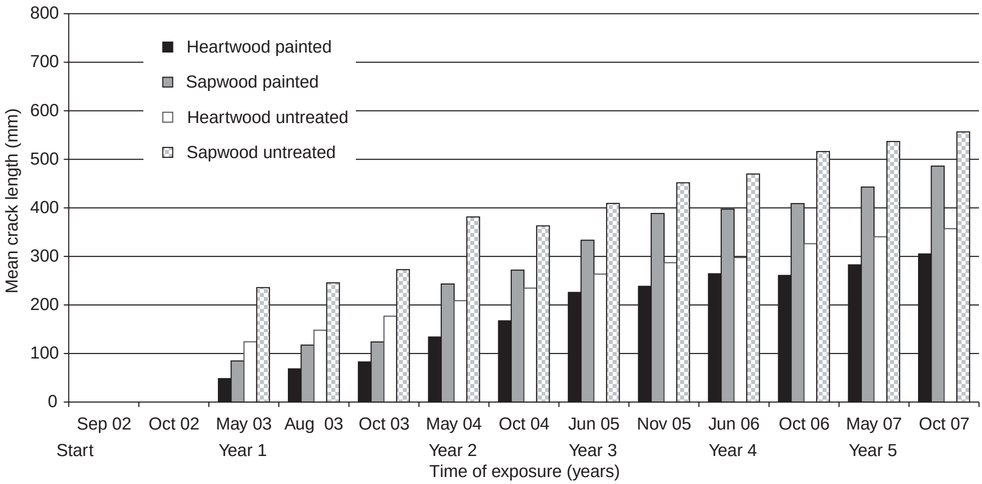

Figure 5. Mean crack length on the 50 × 300 mm lower surface of spruce specimens from 2002 to 2007.

nificantly shorter mean crack length between heartwood and sapwood for both the untreated specimens and the painted specimens from May 2004 to 2007. The difference was significant, but small, especially at the beginning of the exposure.

Site

Further analysis depending on site and tree growth (test groups in Table I: wet suppressed, dry suppressed, wet dominant and dry dominant) shows a difference in mean crack length for untreated upper surfaces (Figure 6). The results from this study, with a limited number of specimens, show that the untreated sapwood specimens from the dry site tend to crack most and the ones from the wet site least.

For untreated heartwood, there was no significant difference in mean crack length on the upper surfaces of the test groups from 2003–2007. There was a significant difference between the test groups in mean crack length on upper surfaces of untreated sapwood from 2003–2007. Mean comparison with Tukey–Kramer HSD showed that the untreated wet suppressed group differed from the other groups and differed significantly from the dry dominant group from 2003–2007.

The trees from the dry site were old with a high density (Table I), and growth rate had diminished with a mean annual ring width of 0.5 mm for the last

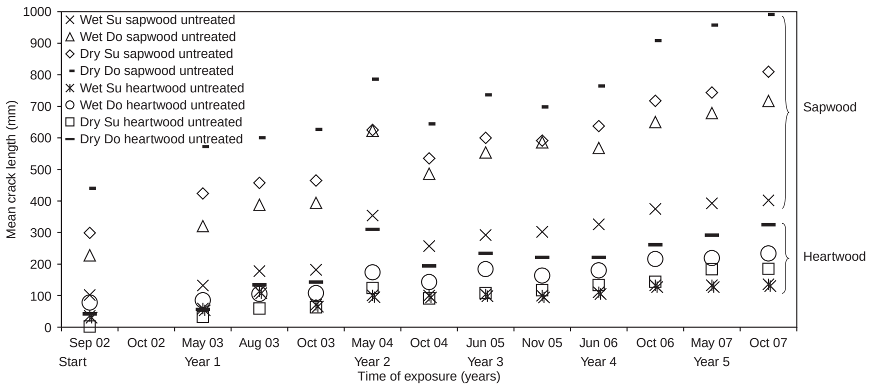

Figure 6. Mean crack length on the 50 × 300 mm untreated upper surface of spruce specimens from 2002 to 2007.

10 years compared to 1.2 mm (suppressed) and 1.8 mm (dominant) for the trees from the wet site.

For painted heartwood and sapwood, there was no significant difference in mean crack length between the sites (not shown). Nor was there any difference in mean crack length on the lower surfaces of the specimens that could be related to the sites (not shown). The main difference was due to heartwood and sapwood, and the sites had less influence.

Visual evaluation

Visual changes on painted and untreated upper surfaces. After 2.5 years, some knots started to be visible through the paint, and on some of the specimens, latewood grain rose above earlywood. Through the years, the width and depth of the cracks increased, and some of the end-grain cracks penetrated through both surfaces. After 3.5 years, it was possible to divide the objects into three groups according to the criteria in Table II (third and fourth columns). Figure 7 shows examples from the three groups for untreated and painted wood.

In group 1, heartwood test specimens were predominant. In group 3, sapwood specimens were predominant. In group 2, heartwood and sapwood were mixed according to the criteria in Table II. This was valid for both untreated and painted surfaces. Figure 8 shows the mean score for heartwood and sapwood from the visual evaluation of upper surfaces, point rating according to Table II. Untreated and painted sapwood had the highest score, and untreated and painted heartwood the lowest.

After exposure for 5.5 years, there were a few test pieces with no or very few cracks and little discoloration on the lower surface, and these were all from heartwood. In the same way, specimens with a lot of discoloration fungi on the lower surface and cracking on the upper surface and end grain were all from sapwood. This trend was clear from the first evaluation after 1.5 years' exposure and remained during the whole test period. Green algae increased on the untreated upper surfaces after a rainy and warm summer season in 2007.

Discoloration of lower surfaces. painted and untreated upper surfaces. After 1.5 years' exposure it was possible to divide visually the specimens into three groups according to discoloration criteria in Table II (first and second columns). Figure 9 shows examples of discoloration on the lower surfaces from groups 1 and 3, with untreated and painted top surfaces. Discoloration along the latewood in annual rings was typical for test objects in group 2.

There were more heartwood specimens in group 1 and more sapwood specimens in group 3, for both untreated and painted specimens. For mean scores from visual evaluation of discoloration separated into heartwood and sapwood, see Figure 10.

The coverage and density of growth did not change remarkably after the first evaluation after 1.5 years. All surfaces became greyer owing to moisture, contamination and dirt, and therefore the scale of greying between the groups became less obvious with time. After about 3 years' exposure, the almost black discoloration faded after a dry and hot summer.

Microscopic analysis

The lower surface discoloration was mostly due to *Aureobasidium pullulans*, together with a few other discolouring fungi, green algae, white algae and dirt. Yellow spots were found to be an unidentified kind of fungus. The fibres on the upper surfaces were damaged by weathering, and *A. pullulans* was found. The grey surface was superficial. The wood that was

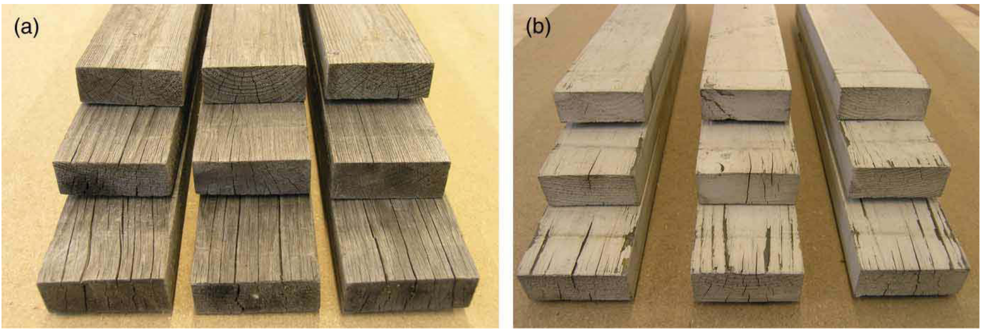

Figure 7. Upper surfaces of samples from (a) untreated and (b) painted spruce. Characteristics of group 1 (top), group 2 (middle) and group 3 (bottom), according to Table II. Photograph: October 2007, after 5.5 years' exposure.

Figure 8. Mean score from visual evaluation of upper surfaces for sapwood and heartwood. Point rating according to Table II.

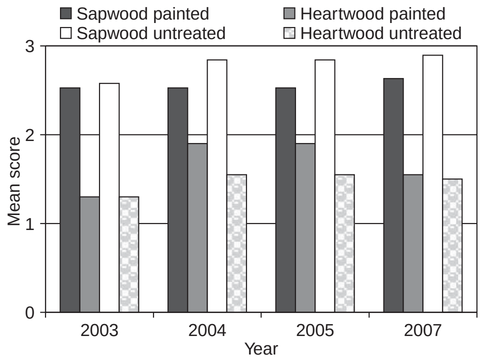

Figure 10. Mean score for sapwood and heartwood from visual evaluation of discoloration of lower surfaces. Point rating according to Table II.

revealed under the test pieces looked yellow and sound, except for one specimen that had blue-sap stain going into the wood.

Aureobasidium pullulans was found on untreated upper surfaces. Of the five untreated test pieces examined in 2007, basidiomycete hyphae were found on one upper surface, soft rot on three and only *A. pullulans* on one, and no rot. On the end grain of these five test pieces, basidiomycete hyphae were found on two, brown rot on three, soft rot on one and only *A. pullulans*, and no rot, on one. In this early stage of decay, it can be difficult to determine what kind of decay basidiomycete hyphae will cause.

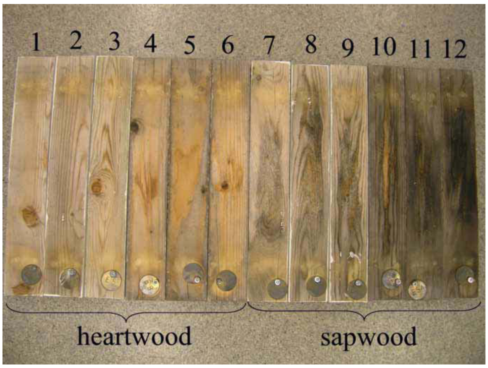

Figure 9. Lower surfaces of specimens with untreated and painted top surfaces of spruce. Test specimens from the left: 1–3 = the three best in group 1 (Table II), slightly affected; 4–6 = the three best from the untreated group 1; 7–9 = the three painted with most discoloration from group 3; 10–12 = the three untreated pieces with the most discoloration. Photograph taken after 2.5 years' exposure.

Discussion

Cracks on upper surface

Cracks that developed in heartwood of spruce were significantly shorter and fewer than cracks that developed in sapwood under the same conditions. There was also a difference in crack distribution and formation between heartwood and sapwood, as evidenced by the visual evaluations of the upper surfaces based on the criteria in Table II. Specimens from heartwood dominated in group 1, and sapwood dominated in group 3, which gave a lower mean score for heartwood. Specimens from the same tree could be sorted into group 1 for heartwood and group 3 for sapwood, i.e. heartwood reduces the formation of cracks.

For the untreated sapwood specimens, there were some differences in crack length depending on growth and site according to test groups in Table I (wet suppressed, dry suppressed, wet dominant and dry dominant). The untreated sapwood grown on a dry site was more predisposed to cracking than the sapwood from a wet site (Figure 6). This may be explained by a high share of latewood in the periphery of the sapwood together with moisture-related movement on the untreated sapwood surface. Latewood shrinks and swells more than earlywood, and in the tangential direction, high stresses arise in and between latewood and earlywood layers, making this a weak region in the wood structure (Sandberg & Söderström, 2006). Sandberg (1999) found on the microlevel that the cracks on the tangential surfaces occur frequently in earlywood and latewood of spruce, and delamination in the middle lamellae is especially noticeable in the latewood after weathering. In old trees, narrow annual rings form in the periphery of the trunk, i.e. the sapwood can have a high proportion of latewood (Kollman, 1982).

The trees from the dry site were old; their growth rate had diminished and they had thinner annual rings compared to heartwood. The untreated surfaces are subjected to more moisture-related fluctuation than painted surfaces, since rain wets the untreated surface more rapidly. The untreated surface dries more quickly in the sun, and that causes high stresses and thus increased cracking. The difference between heartwood and sapwood is probably that heartwood absorbs less water and undergoes slower moisture-related fluctuation.

Cracks on lower surface

Mean crack length was greater on the unexposed lower surfaces of the heartwood specimens than on the upper surfaces (Figure 4 and 5). Sandberg and Söderström (2006) found no significant difference in mean total crack length per area unit between tangential sections with inside and outside faces (pith and bark side) exposed, in either spruce or pine. Rowell (2005) writes that on flat-grain surfaces, checking occurs predominantly on the bark side and raised grain on the pith side, which coincides with the results in this investigation.

Cracks tend to transport water into the wood and gather dirt and moisture, thereby increasing the risk of decay and reduction of strength. In this test, the specimens with many cracks in or close to the end grain became brittle and fragile. Since nail and screw joints are very often made close to ends of wood boards, joint strength can be endangered in the long run. For this reason, all treatment of wood that makes wood brittle and easy to crack should be avoided in outdoor use. In addition, cracks are an aesthetic liability.

Visual inspections of upper surfaces

After 3.5 years, a change was observed on previously fairly intact painted surfaces in the form of crack development, knot bleeding and paint starting to loosen. After 5 years, paint was loose along bands of raised latewood, which can be seen in group 3 in Figure 7(b). The reason for this may be that in specimens with horizontal annual rings, there is a large difference in density between earlywood and latewood. On wetting and the resulting raising of grain, the paint is subjected to tension at zones close to the transition between earlywood and latewood, and it may therefore crack and delaminate.

Another factor contributing to the loosening of the paint may be that the paint does not adhere sufficiently well to the earlywood. Tests have shown that acrylic paint does not penetrate into the earlywood of spruce, but rather lies on the surface (Miniutti, 1963; de Meijer et al., 1998). It should be borne in mind that in order to speed up the results in this investigation, the best possible surface treatments were not chosen, and no primer was used.

The specimens in the present investigation which still had relatively intact colour coats after 5.5 years and lacked cracks in the end grain came from heartwood.

Discoloration on lower surfaces

From the first evaluation after 1.5 years' exposure, some of the specimens were almost black with discoloration while others had almost no discoloration. There was typically less discoloration on heartwood. For pine sapwood, this phenomenon has to some extent been explained as due to drying at higher drying rates, and relocation and transport of nutrients and sugar to the surfaces that serve as food for fungi and make wood more susceptible to microbial attack (Theander et al., 1993; Terziev et al., 1993; Terziev & Nilsson, 1999).

In spruce heartwood, the transport of nutrients to the surfaces during drying is probably not possible to the same extent owing to low water content in green wood, 34–40% in heartwood compared to 113–153% in sapwood. In addition, the highest concentration of sugars is found near the bark and diminishes towards the centre of the tree. The distribution of protein in the cross-section of the trunk is similar to that of sugar (Fengel & Wegner, 1989). Heartwood of spruce is a less favourable substrate for fungi, which may explain some of the problems with discoloration on boards, for example, on building façades, that are striped with blue sap fungi on one side but not on the other.

Durability and service life

As previously stated, degradation of wood is a complex process involving interaction between wood, the blend of microorganisms, climate and moisture content, exposure time, surrounding environment, etc. Decay and weathering can be unevenly distributed on specimens or invisible to the naked eye. Since the environmental requirements of fungi vary, fungal growth will vary depending on the limitations in environmental factors prevalent. The fungus with the greatest tolerance to the limitations of the environment can continue to grow and will dominate. Decay above ground does not develop in a smooth continuum from year to year. De Grooth and Highley (1995) found that that in some years, substantial bursts of decay occurred after a period of lag in development, while in other years, decay showed little progress above ground. Therefore, the performance of wood and its service life for products in exterior use will be greatly affected by construction practices and degrees of protection from prolonged wetting. However, outdoor exposure above ground shows the interaction between wood, fungi, climate and other environmental factors that influence weathering, and gives a relative comparison between the specimens in the same test.

Visible cracks and discoloration usually appear within a year or so in exterior wooden products. Although this effect is mainly an aesthetic consideration initially, with time, cracking and decay can become severe enough to reduce the strength of the construction. Therefore, the effects of long-term exposure must be considered.

The differences in cracking and discoloration between spruce heartwood and sapwood can be explained by the lower liquid water absorption in heartwood (Sandberg, 2006) and by the faster drying of heartwood, which undergoes lesser moisture-related movements and is thus a worse substrate for fungi than is sapwood. A different chemical composition between heartwood and sapwood, and between earlywood and latewood (Bertaud & Holmbom, 2004), may also contribute to the difference, but how this may affect weathering has not been investigated.

Conclusions

Outdoor exposure for 5.5 years showed that spruce heartwood exhibits significantly less surface cracking and discoloration growth on the lower surface compared to sapwood. This investigation shows that painted heartwood has the shortest crack length, and untreated sapwood the longest crack length, on both the upper surfaces and the lower surfaces of the specimens. The main cause of the difference in the rate of degradation between heartwood and sapwood would seem to be that heartwood of spruce absorbs less water than sapwood and thus is less subject to moisture-related movements in the wood.

To improve performance and to produce uniform and high-quality products for outdoor use, such as façades, it is of great importance to utilize the properties of spruce heartwood more effectively to avoid cracks and discoloration. The natural resistance of spruce heartwood to the growth of blue sap stain is also important for building products in general.

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VII

Separating Norway spruce heartwood and sapwood in dried condition with near-infrared spectroscopy (NIRS) and multivariate data analysis

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Abstract

Norway spruce (*Picea abies* (L.) Karst.) heartwood and sapwood have differing wood properties, but are similar in appearance. An investigation was made to see whether near-infrared spectroscopy (NIRS) could be used with multivariate statistics for separation between heartwood and sapwood in dry state on tangential longitudinal surfaces. For classification of wood into sapwood and heartwood, partial least square (PLS) regression was used. Orthogonal signal correction (OSC) filtering was used on the spectra. This study shows that a separation of sapwood and heartwood of spruce is possible with NIR spectra measured in a laboratory environment. The visible-wavelength spectra have significant influence on the predictive power of separation models between sapwood and heartwood of spruce. All 44 specimens in the calibration set were correctly classified into heartwood and sapwood. Validation of the model was done with a prediction set of 16 specimens, of which one was classified incorrectly.

***Keywords**: near infrared spectroscopy, PLS, heartwood, sapwood, Picea abies, heartwood content*

Introduction

The properties of Norway spruce sapwood and heartwood differ from one another, though the two are visually quite similar. For instance, spruce heartwood absorbs less water in end grain and dries faster than sapwood (Sandberg 2002; Sandberg 2006). Less sorption results in less free water in the wood and means that the wood is less conducive to fungal growth, is less subject to moisture-induced deformations and cracks (Sandberg 2008) and less subject to the growth of discoloration fungi (Sandberg 2008; Bergström *et al.* 2005; Blom & Bergström 2005; Frühwald 2007). These properties are important for attaining a long service life in aboveground conditions. A separation of heartwood and sapwood can also be of use in the pulp and paper industry, seeing that wood properties vary in the radial cross-section. Additionally, a separation of sapwood and heartwood can be of interest in better understanding the physiological aspects, *e.g.*, sapwood as a conductive area for water in the stem through which the crown of the tree (foliage) gains access to water. Larger sapwood volumes have been correlated with larger quantities of foliage (Bügsen & Münch 1929). Index of vigour, for which sapwood is one of the parameters, can be an indicator of tree growth, health and the effects of environmental factors (Münster-Swedsen 1987). The heartwood content in trees generally increases with age, but there is considerable variation due to environmental and site conditions as well as genetic control (Hillis 1987; Taylor *et al.* 2002).

It is difficult to separate Norway spruce heartwood from sapwood with the naked eye. To delineate sapwood and heartwood in green wood, Münster-Swendsen (1987) tried four methods: differences in natural colours, differential translucence, use of an aniline pencil and application of methyl red dye. The differential translucence method, in which thin cross-sectional discs are held up to the sky and the border is marked with a pencil, proved to be the best method. Nondestructive scanning with ionizing radiation (x-rays and γ-rays) and computer tomography (CT) images of the inner parts of logs (Bucur 2003) provide new opportunities. Heat-sensitive infrared imaging on the cross-section has been tested on pine (Gjerdrum & Høibø 2004). Infrared imaging and CT scanning distinguishes the difference between heartwood and sapwood based on moisture content variations. A database for different silvicultural and wood properties based on CT scanning data on logs was established (Grundberg *et al.* 1994) for the development of software and algorithms for simulations. For instance, CT scanning and algorithms for separation of heartwood and sapwood of spruce have been developed by Longuetaud *et al.* (2006, 2007).

For the industry to utilize the better properties of heartwood to produce more durable products with even quality, such as cladding, it is necessary to identify and separate heartwood and sapwood during processing in sawmills. In order to secure nearly 100% heartwood in the products, it is necessary to be able to define the border between heartwood and sapwood. Simulations have shown that it is possible to sort spruce heartwood by X-ray scanning with a LogScanner in log sorting or with laser technique in the green sorting line (Grundberg 1999; Oja *et al.* 2001; Oja *et al.* 2006).

These methods measure differences in moisture between heartwood and sapwood. A method to classify heartwood and sapwood on dry spruce wood is, however, still missing.

Near-infrared spectroscopy (NIRS) has been used in many fields, such as food, pharmaceutical applications and spectroscopy of polymers and wood. The near-infrared technique is based on electromagnetic radiation. NIRS includes wavelengths ranging from 750 nm to 3000 nm. Absorption in this range occurs due to the presence of water, organic compounds and various chemical bonds. A new review of NIRS research involving wood and paper has been done by Tsuchikawa (2007). Investigations on wood show that it is possible to classify pine heartwood and sapwood correctly with partial least square (PLS) regression models (Flæte & Haartveit 2003). Differentiation between three Picea species that have similar visual appearance but different mechanical properties has been demonstrated by Flæte *et al.* (2006). Various investigations have used NIRS for prediction of such wood properties as stiffness, density and fibre length (Hauksson *et al.* 2001; Schimleck *et al.* 2003; André *et al.* 2006). Predicting wood decay by using NIR was reported by Stirling *et al.* (2007) and Fackler *et al.* (2007), and prediction of natural durability was reported by Sykacek *et al.* 2006.

The aim of the present work was to investigate whether NIRS and multivariate statistics can be used for separation of heartwood and sapwood of Norway spruce (*Picea abies* (L.) Karst.) in dry state.

Materials and Methods

Logs from 30 Norway spruce (*Picea abies* (L). Karst.) were taken from three sites at Vindelns's Experimental Forest in northeast Sweden (64°13' N, 19° 41'E). The sites differed from each other with respect to supply of water. One site had a good supply of water (wet), and the other site was without free ground water (dry). Half of the trees have grown suppressed and half of them dominant, *i.e.*, five trees in each group. Five trees were irrigated (I) with water and nutrients for 15 years, and 5 trees came from a control group (C) without irrigation. Stem discs were cut at 5.25-m height from the butt cut for specimens from wet and dry sites. Specimens from irrigated and control sites were taken 0.25 m from the butt cut because of the small diameter. The heartwood /sapwood border was marked with a highly water-resistant permanent marker on the stem disc in the forest in frozen condition. When spruce is frozen, the border is easy to distinguish, and heartwood appears as white while sapwood appears as yellow. The discs were stored in a freezer in plastic bags until CT scanning and the manufacturing of specimens. Characteristics for the trees were determined on the stem discs and are shown in Table 1. By scanning the stem discs' cross-sections, the annual ring width and age were calculated with image-analysis software application in house. Density and heartwood content were determined from CT images and image processing in a software program (Scion Image). A CT scanner, Siemens SOMTOM AR.T, located at Luleå University of Technology was used for the measurements.

Table 1 Data for the test trees. Mean values of five trees in each group and standard deviation. Characteristics: age of trees (Age), annual ring width ($Ring_{width}$), density at moisture content (MC) 12% ($Density_{12\%}$), diameter at breast height with bark (dbh), height of the tree (Height), heartwood content ($Heart_{cont}$) *i.e.*, area heartwood/total cross-section of the stem discs without bark.

Site	Age (years)	$Ring_{width}$ (mm)	$Density_{12\%}$ (kg/m^3)	dbh (cm)	Height (m)	$Heart_{cont}$
Wet suppressed	67 ± 8	1.5 ± 0.3	414 ± 38	19.1 ± 1.3	18.3 ±1.4	0.37 ± 0.08
Wet dominate	66 ± 2	2.6 ± 0.2	395 ± 30	30.7 ± 0.8	21.8 ±2.1	0.36 ± 0.07
Dry suppressed	137 ± 25	0.6 ± 0.2	491 ± 28	17.9 ±1.0	14.3 ±1.2	0.50 ± 0.05
Dry dominate	158 ± 10	1.0 ± 0.2	452 ± 39	28.9 ±1.2	22.2 ±1.2	0.59 ± 0.05
Irrigated (I)	37 ± 0	2.0 ± 0.2	361 ± 21	15.8 ±1.3	9.8 ± 0.6	0.39 ± 0.05 *
Control (C)	36 ± 0	1.7 ± 0.1	410 ± 14	12.9 ±1.0	8.9 ± 0.3	0.12 ± 0.19

* In those young trees, the border between heartwood and sapwood is less distinct, and therefore intermediate wood was included in the heartwood area which gives overestimated heartwood content.

Specimens were taken from the south side of the stem discs. Specimens with dimensions 5 x 35 x 45 mm were taken from sapwood and heartwood (see Figure 1). Specimens were dried and conditioned to 13% moisture content (MC) in a climate chamber. Before measurement, the surface was slightly roughened with sandpaper. In all, 30 sapwood and 30 heartwood specimens were prepared.

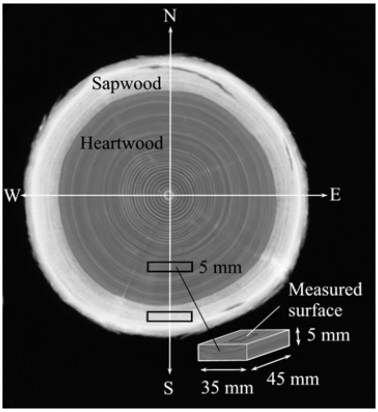

Fig 1 Cross-sectional computer tomography (CT) image of stem discs in green state 5.25 m from butt cut showing specimens for NIR analysis in heartwood and sapwood. In CT images, the intensity in grey scale is proportional to density; therefore heartwood appears as dark grey and sapwood as white

NIR

NIR measurements were performed with a FOSS NIR SYSTEM 6500, which uses wavelengths from 400–2500 nm with a step of 2 nm, resulting in 1050 measuring points. The specimens were placed in a holder, and the ray was moved over a surface 30 mm wide and 8 mm high in the middle of the specimen (Figure 1). Measurement was carried out in reflectance mode, and the spectra are composed of the absorbance value for each wavelength.

Multivariate Data Analysis

The NIR spectra were imported into the multivariate software SIMCA-P+11 (Umetrics AB 2005) for pretreatment (filtering) and analysis. A data set was composed of 60 observations consisting of spectra with absorbance at 1050 wavelengths. These spectra were used as predictors (X-variables) in the multivariate analysis and were centred, but not scaled, since they all were spectroscopic data on the same scale. Analysis was conducted according to recommendations in Sundberg (1999) and Eriksson *et al.* (2001). Responses (Y-variables) were heartwood and sapwood, which were two classes. In the data set, “0” stands for sapwood and “1” stands for heartwood. Heartwood and sapwood were centred and scaled to unit variance according to default value in SIMCA.

The NIR spectra used in this investigation were preprocessed with an orthogonal signal-correction (OSC) filter, which was also described in Eriksson *et al.* (2001). OSC removes undesirable systematic variation in the data and improves models’ properties. Such undesirable systematic variation might be, for instance, baseline drift, multiplicative scatter effects and wavelength regions of low information content. For development of models, projection to latent structures by means of partial least squares (PLS) regression was used as described in Eriksson *et al.* (2001).

The 60 observations were divided into two sets: calibration and prediction set for validation. In the calibration set, 22 sapwood and 22 heartwood spectra were used. In the prediction set, 8 sapwood and 8 heartwood spectra were chosen at random. The calibration set was used to develop models, and the prediction set was used for external validation of the predictive power of the models.

To evaluate the models, R^2Y(cum), Q^2(cum), Q^2(extern), RMSEP and number of correct classifications were used to constitute model diagnostics parameters describing the robustness of the model (Ericsson *et al.* 2001). Small differences between explained variance R^2Y and predicted variance Q^2Y indicate stable models that are not modelling noise. R^2Y(cum), called the goodness of fit, explains the variation of Y data. R^2Y(cum) represents the cumulative sum of squares (SS) of the Y explained by extracted components. R^2Y is computed as 1-SSE/SS, where SSE is the sum of square errors. Q^2(cum), or goodness of prediction, indicates predictive ability and represents the cumulative cross-validated R^2. Cross-validation (Wold 1978) is a method to determine the number of significant principal components (PC) in the model. This prevents the model from being underfitted and all information not being used, or overfitted with too many PCs and variation in the data due to random relations (Martens & Naes 1996). In cross-validating, observations are left out during model calculation and then later predicted one at a time. The Predicted Residual Estimated Sum of Square (PRESS) can then be used for computing the goodness of prediction. Q^2 is computed as (1.0 - PRESS/SS).

To validate the model made by the calibration set, the external prediction test set is used to compare the observed values with predicted samples. Q^2(extern) represents the correlation between Y predicted by model and Y observed (true) in the prediction set.

RMSEP is the root mean square error of prediction and represents the standard deviation of predicted residuals (Ericsson *et al.* 2001) between observed and predicted test set values and is calculated as

$$RMSEP = \sqrt{\frac{PRESS_{predset}}{Number_{pred \cdot samples}}}$$

Results

Two models with OSC filtering of the spectra and evaluated using PLS regression for classification into heartwood and sapwood are presented here. Model M1 was obtained with wavelengths of 400–2500 nm, *i.e.*, including visible wavelengths, and M2 was obtained with 700–2500-nm wavelengths, *i.e.*, visible wavelengths excluded. Model diagnostics are shown in Table 2.

Table 2 Model diagnostics. PC (number of component for the calibration model), R^2Y(cum) (explained variance of Y-data), Q^2(cum), predicted variance, Q^2(extern) predicted variance prediction set, RMSEP, standard deviation of predicted residuals.

Models	Wavelength (nm)	PC	R^2Y(cum)	Q^2(cum)	Q^2(extern)	RMSEP
			Calibration set		Prediction set	
M1. Visible band	400–2500	1	0.954	0.95	0.6839	0.2898
M2. No visible band	700–2500	1	0.7	0.69	0.1	0.5

As shown in Table 2, Model M1 has very high R^2Y(cum) and Q^2(cum) of 0.95. This indicates that the model describes 95% of the variability in Y data. Figure 2 shows the prediction of observations in model M1 with calibration set into heartwood and sapwood obtained with cross-validation. The model managed to predict all observations correctly into heartwood and sapwood when Ypred = 0.5 was used as a threshold for separation. All sapwood observations were predicted with values lower than 0.5 and all heartwood observations were higher than 0.5. Observations that lay on the right side of the given threshold were considered to be correctly classified.

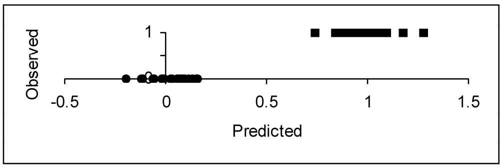

Fig 2 Prediction of observations in model M1's calibration set into heartwood (1) and sapwood (0), plotted as observed versus predicted

In order to test if model M1 can correctly predict new observations, the prediction set was used. In Figure 3, the values predicted by model M1 are plotted against true values from the prediction set. 15 of 16 observations were correctly classified, since only one heartwood specimen was predicted as sapwood.

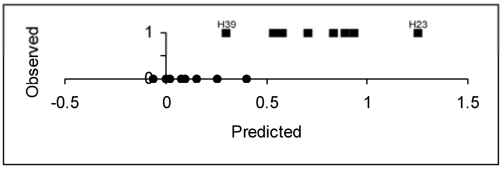

Fig 3 Values predicted by model M1 are plotted against true values from the prediction set, heartwood (1) and sapwood (0)

By mistake, one test object had not been in the climate chamber before measurement and had an MC of 11.6% (compared to 13% for all the others), H23 to the right in Figure 3. This observation is correctly classified, but with a deviating behaviour. It is known that water absorbs energy in the NIR spectrum bands, and therefore the presence of water has an impact on the models. The moisture content of wood thus has to be considered.

Test object H39, to the left in Figure 3, was predicted as sapwood which could contain some root rot. Root rot can probably affect the models through colour and structural changes. This can affect the predictability of the models in such a way that colour, chemical composition and reflectance are different compared to the other specimens in the calibration set**.**

In this study, specimens were manufactured in the laboratory with smooth, even surfaces, and the measurements were done on the tangential longitudinal surface. However, three of the specimens (S56, S46, S60) by accident had grain direction perpendicular to the direction of measurement instead of parallel. Apparently, this had no influence on the OSC models or predictive power; all observations were within the models (Figures 2 and 3).

Model M2, without visible wavelengths, had lower predictive power, Q^2(cum), than Model 1 (Table 2). Figure 4 shows the prediction into heartwood and sapwood of observations in the calibration set for model M2, obtained by cross-validation. The separation is not absolute; 41 of 44 observations were correctly classified, and two heartwood specimens were predicted as sapwood and one sapwood specimen was predicted as heartwood.

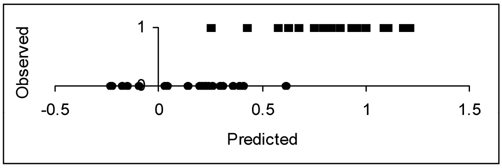

Fig 4 Prediction of observations in the calibration set for model M2 into heartwood (1) and sapwood (0)

In Figure 5, the values predicted by model M2 are plotted against true values from the prediction set. 12 of 16 observations were correctly classified; two heartwood observations were predicted as sapwood and two sapwood observations were predicted as heartwood. The addition of visible wavelengths improved the prediction power of the models significantly. This implies that the colour of the sapwood and heartwood is not the same and that it influences the models to a great extent.

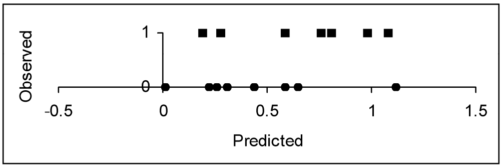

Fig 5 Values predicted by model M2 are plotted against true values from the prediction set, heartwood (1) and sapwood (0)

Wavelengths

Wavelengths that are important for discrimination of heartwood are shown in Figure 6. Figure 6 shows raw regression coefficients obtained from PLS models computed on NIR calibration spectra of Model 1. The regression coefficients of the model are used to construct the predictions and determine important spectral regions that are responsible for correlation for separation heartwood and sapwood. The wavelengths with the most impact on the model were within 2400–2500 nm, 430–450 nm, 2300–2370, 1940–1950, 2110–2150 and 1456–1498 nm, listed in order of importance.

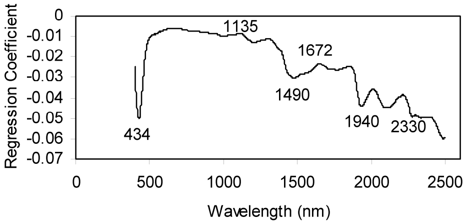

Fig 6 Regression coefficient from the PLS regression of the NIR spectra for separation of heartwood of spruce

Discussion

All observations in the calibration set were separated correctly into sapwood and heartwood according to Model 1, which included visible wavelength bands (see Figure 2). Model M1 can predict new observations, and in this case, 15 of 16 observations from the prediction set were correctly classified (Figure 3).

It must be emphasized that our data set was limited to specimens from 30 trees (60 specimens). However, those trees were chosen from different sites with different properties such as age, density and diameter (Table 1). The trend from our investigation is clearly that it is possible to correctly classify spectra measured on dried spruce heartwood and sapwood. The visible spectrum contributes to the model and has an important impact on the models. Flæte & Haartveit (2003) found that it was possible to correctly classify heartwood and sapwood of Scots pine with no visible colour differences, but exclusion of the visible region (400 to 780 nm) made the model weaker and increased the number of principal components needed in order to correctly classify all samples.

To the human eye, there are no visible differences in colour, but the visible spectrum has an obvious impact on the models and therefore needs to be evaluated. Possible reasons may be the influence of differences in chemical content or structural differences such as density, annual-ring width and presence of early- and latewood.

For interpretation of the relation of NIR wavelengths to specific wood components that contribute to separation of heartwood and sapwood, results from other investigations have been used, since chemical compositions were not investigated in this study. However, according to Figure 6, the wavelength intervals with the greatest impact on the model were 2400 to 2500 nm, which might be due to differences in organic substances as cellulose, starch and protein (Shenk *et al.* 2008), and thereafter 430 to 450 nm (visible light), which reflects blue colour.

The colour difference between sapwood and heartwood detected by NIR measurements is not visible to the human eye. It may be caused by differences in chemical composition that secondarily cause colour differences and are correlated with them (Curran 1989).

The wavelengths around 1940 nm are probably due to water (Shenk et al. 2008; Curran 1989; Tsuchikawa *et al.* 2004). Absorbing compounds for wavelengths around 2330 nm and 1490 nm are probably cellulose, hemicellulose or starch (Shenk *et al.* 2008; Curran 1989; Tsuchikawa 2004; Schwanninger *et al.* 2004). Lignin compound is associated with wavelengths around 1135 nm and 1672 nm (Tsuchikawa 2004). With respect to regression coefficients (Figure 6), this means that together with the visible wavelengths, the ability to separate heartwood and sapwood is manly due to there being less cellulose and hemicellulose content and more lignin in heartwood. Bertaud & Holmbom (2004) found that spruce heartwood contained significantly more lignin and less cellulose than sapwood. According to Fengel & Wegner (1989), the highest concentration of sugars is found near the bark and diminishes towards the centre of the tree.

Other investigations show that the amount of extractives in spruce is rather small compared to other wood species and varies between 0.5% and 4.2% of dry weight (Lindgren & Norin 1969; Pensar 1967; Assarsson & Åkerlund 1966). The fatty acid concentration is higher in the sapwood (1%–4% compared to about 1% in heartwood) and decreases towards the pith (Pensar 1967; Ekman 1980). Ekman (1980) found that radial distribution of resin acids and diterpene alcohol showed similar, but weaker, trends, and the differences between sapwood and heartwood were much smaller.

Though the chemical differences between heartwood and sapwood are relatively small, they may yet affect the surface colour of spruce. Sundqvist (2002) found that untreated heartwood of spruce had a significantly brighter and yellower surface than sapwood as measured with a photoelectric colorimeter. Tsuchikawa et al. (2004) suggest that degradation of CH in the aromatic skeletal region due to lignin and in the furunose or pyranose region due to hemicelluloses could easily occur during light irradiation and contribute to the yellowing of wood samples.

Many factors have to be considered and included in the calibration set in order to construct a viable prediction model. Further work needs to be done for verification of the impact of colour, moisture content, density and chemical content on the models. Considering the influence of the visible wavelength spectrum on the separation process, since the colour may be influenced by moisture content, which can vary widely, this may entail problems for industrial use. Therefore, a laboratory application is much more realistic. Optical properties change with moisture content (Oja *et al.* 2006), and NIR measurements will be influenced by variations in temperature (Shenk *et al.* 2008). Another aspect that has to be considered is whether the method will be able to separate heartwood and sapwood on surfaces with varying degrees of roughness. In this study, specimens were manufactured with smooth, even surfaces.

Conclusions

This study shows that separation of spruce sapwood and heartwood in dry state is possible with NIR spectra measured in a laboratory environment. The visible wavelength spectrum has a significant influence on the predictive power of models for separation between sapwood and heartwood of spruce. Without this wavelength spectrum, no satisfactory models could be obtained with the present data set.

Acknowledgments

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Production of Heartwood Products – Effects on Volume Yield

Abstract
Research has shown that Norway spruce (*Picea abies*) heartwood has slower water absorption, slower growth of discoloration fungi and less crack formation compared to sapwood. These properties are important for attaining a long service life for wood products subjected to water, moisture or sunlight and make Norway spruce heartwood suitable for outdoor products, for example, paneling or windows. This study has utilized saw simulation technique combined with detailed information from 750 logs in the Spruce Stem Bank in order to select appropriate logs for production of heartwood products and analyze effects on volume yield in comparison to regular production conditions. Production of three heartwood center-board products was evaluated.

This study has analyzed effects on volume yield, established favorable log diameter intervals for three individual products and evaluated measures to compensate for volume yield loss. Conclusions are that production of Norway spruce heartwood products can be efficient, but is in need of an improved log sorting process, logs with a larger top diameter and alternate breakdown rules in comparison to normal production. Effects such as volume yield and production output losses can be compensated by extracting more side boards and by achieving higher sales prices. It has furthermore been shown that x-ray technique in combination with breakdown simulation is an adequate tool to select appropriate logs and to find measures of compensating for volume yield losses caused by altered breakdown rules.

Introduction
The properties of Norway spruce (*Picea abies*) sapwood and heartwood differ from one another, although the two are visually quite similar. For instance, spruce heartwood absorbs less water in end grain and dries faster than sapwood (Sandberg 2006), and the heartwood is less subject to cracks (Sandberg 2008) and growth of discoloration fungi (Sandberg 2008; Frühwald 2007; Bergström *et al.* 2005). Less absorption of water leads to faster drying and thus a shorter wetting time, less moisture-related movement in the wood and worse living conditions for fungi. These properties are important for attaining a long service life in aboveground conditions, as cracks promote water absorption and provide places where dirt can accumulate, thereby increasing the risk of decay and reduction of strength. Apart from that, growth of discoloration fungi and cracks are an aesthetic liability.

Spruce has on average larger heartwood content than pine (*Pinus silvestris*) (Kollman 1982) and that is an advantage looking toward volume yield of heartwood products. Generally, the heartwood content increases with the age of the trees for many species, but there are considerable variations due to environmental and site conditions, genetic control, *etc.* (Hillis 1987; Taylor *et al.* 2002).

For trees of the same age there is a great spread in heartwood content (Eneroth 1922), and this makes it difficult to predict the heartwood content and to ensure 100% heartwood in products for outdoor use (Wilhelmsson *et al.* 2002; Lycken *et al.* 2009).

Spruce is regarded and used as a homogeneous material, and spruce heartwood has not been utilized in products for use in aboveground conditions in a controlled way. One reason for this may be that is impossible to visually distinguish sapwood from heartwood when dried. Today, there are two possible non-destructive industrial techniques to distinguish heartwood of spruce. Both of these methods measure differences in moisture between heartwood and sapwood and are used for pine as well. Visual separation of pine heartwood and sapwood is possible in green state by X-ray LogScanner in timber sorting (Oja & Grundberg 2004; Skog & Oja 2009) or with laser technique in green sorting line (Oja *et al.* 2006). Studies have been done in order to create algorithms for automatic detection of the heartwood/sapwood boundry from x-ray retrieved information (Longuetaud *et al* 2007). Simulations have also shown that it is possible to sort spruce heartwood by X-ray scanning (Oja *et al.* 2001).

Saw simulation technique is an efficient method to study the impact on volume yield caused by log properties or different sawing strategies. Several studies and research projects have been performed in order to create and utilize software imitating a sawmill breakdown process. This technique has been verified and used, for example, by Lundahl (2007), Nordmark (2005), Pinto *et al.* (2002, 2003), Chiorescu *et al.* (2000), Grundberg *et al.* (1999), Todoroki *et al.* (1999), Usenius (1999) and Johansson (1978).

Objectives

The objective of this study was to evaluate the prerequisites to minimize loss of volume yield during production of three given products from Norway spruce heartwood.

Material and methods

Limitations

Knot definitions were deactivated in the simulation software, and equal price was set for all products in order to achieve an explicit volume yield optimization without knot- or price-related influence. Final results presented in this study were achieved from a relatively limited number of logs.

The European Spruce Stem Bank (ESSB)

The European Spruce Stem Bank is a database containing detailed information about 750 logs from Norway spruce trees harvested from 31 different sites in France, Finland and Sweden (Anon 2000). A medical CT scanner (Siemens SOMATOM AR.T) was used to scan the logs. The resulting images from CT-scanning of a log are detailed descriptions of outer shape, heartwood border, location of the pith and a nine- parameter description of the knots. The detailed data stored in the Spruce Stem Bank makes it possible to recreate the outer shape and inner structure of every log using dedicated saw simulation software.

Saw Simulation Software

The Saw2003 simulation software (Nordmark 2005) is a PC-based C++ application developed to utilize the digitized data information contained in the Spruce Stem Bank and is used to simulate the breakdown process using cant-sawing according to the common rules used in Swedish sawmills. The produced boards are graded according to the Nordic Timber Grading Rules (Anon. 1999). The software calculates the volume yield as below:

$$Yield\,(\%) = \left(\frac{\text{Nominal volume of trimmed Boards}}{\text{True Log volume}}\ x\ 100 \right)$$

Nominal volume of trimmed board is the final board volume after drying to 18% moisture content and trimming. True log volume is the green log volume under bark.

Simulation scenario

A scenario for a specific sawmill stated a demand of center-board products (44 x 150 mm, 63 x 150 mm and 63 x 175 mm) with high heartwood content. The center boards are later split into two 21- x 150-mm (44 x 150 mm), three 19- x 150-mm (63 x 150 mm) or three 19- x 175-mm (63 x 175 mm) panel boards before planing and profiling. In the present study, all logs in the Spruce Stem Bank were sorted into 15-mm intervals according to top diameter, and the different intervals were evaluated and compared. Sawing patterns used in step 1, Figure 1, included only 2 center boards; steps 2 and 3 included 2 center boards and 2–4 side boards per log. Sawing patterns used in step 4 included 2 center boards and in some cases up to 10 side boards. In order to optimize yield, the applied sawing pattern must be adapted to the heartwood top diameter in the same manner as sawing patterns commonly are adapted to the log top diameter during normal production conditions, Figure 2.

The present scenario required that approved logs should produce two center boards at full log length containing an allowed share of sapwood on the peripheral edges of the center boards (see Figure 2, scenario b and c), since these parts of the panel will be removed during profiling. A minimum of 4 mm heartwood on the final panel board’s edge side was required.

The study was performed in four steps:

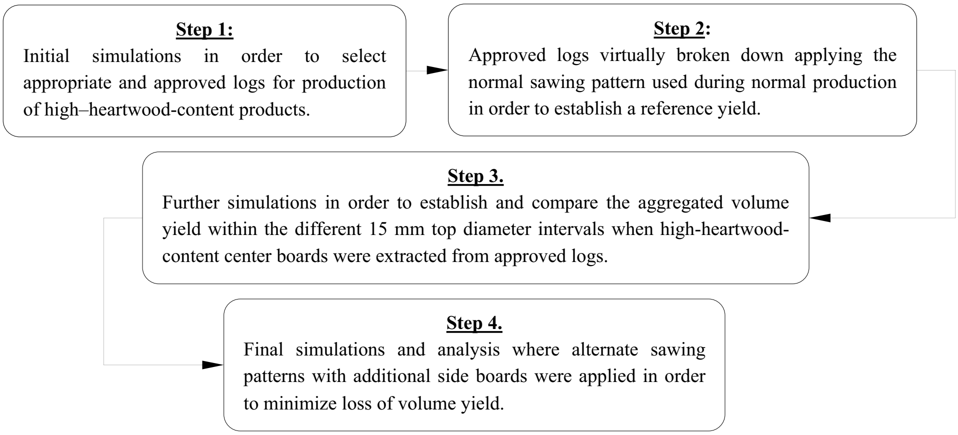

Figure 1. Simulation flowchart of performed steps.

Initially, a number of simulations were performed in order to find appropriate logs for production of panels with high heartwood content (Figure 1, step 1).
For each product, three different scenarios were simulated and evaluated:
<u>Scenario a (step 2, Figure 1)</u>
The reference scenario presented as “Reference (R)” specifies the potential volume yield achieved by sawing the approved logs within the interval under a normal production scenario, applying sawing patterns governed by sawmill rules (Figure 2, scenario a).

<u>Scenario b (step 3, Figure 1).</u>
“Postlist (Hw)” specifies the simulated volume yield achieved when the same logs within the interval were sawn according to the high heartwood (Hw) content scenario, applying one of three different sawing patterns (44 x 150, 63 x 150 or 63 x 175) (Figure 2, scenario b).

<u>Scenario c (step 4, Figure 1).</u>
“Postlist Alt (Hw)” specifies the simulated volume yield achieved when the same logs within the interval were sawn according to the high-heartwood-content scenario, applying an alternate sawing pattern with more side boards added to the basic sawing patterns in order to minimize loss of volume yield (Figure 2, scenario c).

Figure 2 shows the principles for adapting the sawing pattern to logs under normal production conditions in comparison to production of high-heartwood-content products and stated requirement of heartwood on panel side edges.

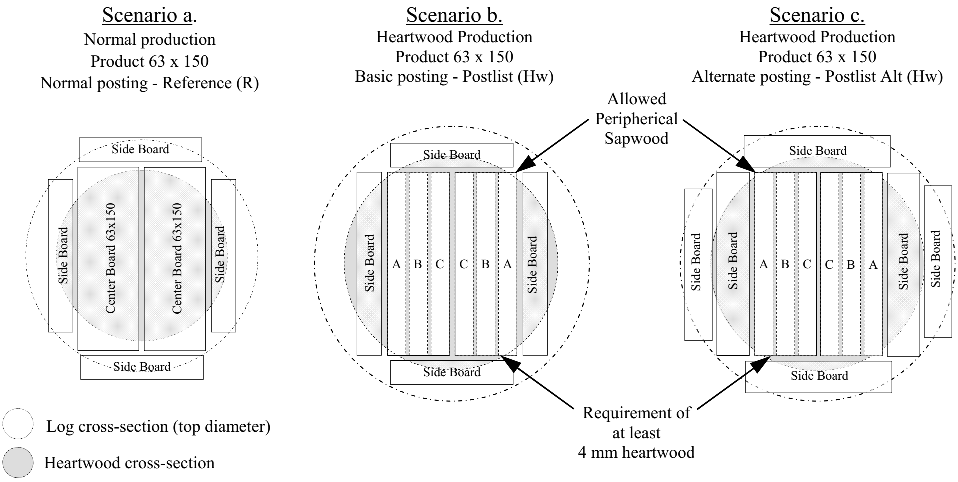

Figure 2. Principles of posting for normal production of product 63 x 150 (scenario a) in comparison to the two evaluated sawing patterns for production of high-heartwood-content products (scenarios b and c). Center boards are split into panels A,B and C after drying (scenarios b and c). Additional side boards are added to the sawing pattern in scenario c in order to maximize volume yield. Sapwood content on panels "A" can be allowed up to a certain limit since these parts will be removed during the final profiling procedure. Requirements of at least 4 mm on the A-panels side edges (scenarios b and c) must consist of heartwood was stated in the scenario. Allowed sapwood and requirement of heartwood content on panel side edges marked by arrows in the figure.

Results

Heartwood content

The heartwood share of logs in the Spruce Stem Bank varies substantially between individual logs, from 16 percent to 89 percent of the log top diameter. The heartwood diameter also varies when comparing two similar logs. For example, two logs in the Spruce Stem Bank show the same measured top diameter, 161.6 mm. However, one log shows a heartwood top diameter of 77 mm, the other one 119 mm. The first log is a butt log harvested in the south of Sweden, the other one a top log harvested in the North of Sweden. Figure 3 shows the log top diameter plotted versus heartwood share of top diameter on 750 individual logs. The R^2-value is relatively high, 0.89 thus indicating a high degree of explanation. However, the prediction accuracy is still too low to satisfy requirements in this study.

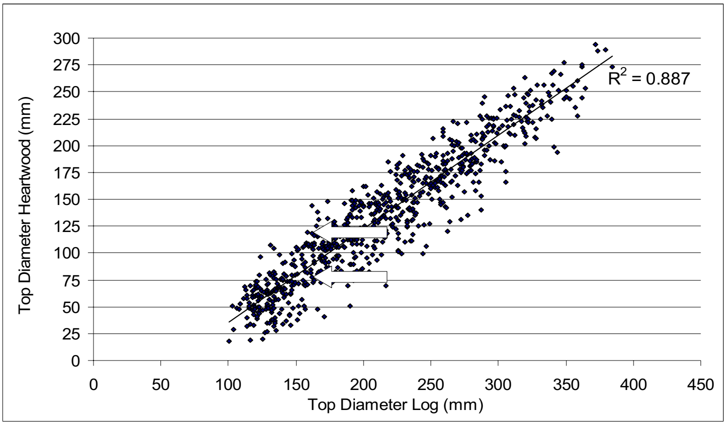

Figure 3. Heartwood top diameter plotted versus log top diameter of 750 logs in the Spruce Stem Bank. Logs with identical top log diameter can show a large spread in heartwood top diameter. Two logs in the Spruce stem bank show the same top diameter, 161.6 mm, but the heartwood diameter is in one case 119 mm and in the other case 77 mm (positions marked by arrows).

Approved logs

The specific requirements in the scenario makes it important to find the exact heartwood diameter for every single log. The simulation results showed that zero approved logs were found in the commonly used top diameter intervals, regardless of product. For example, product 44 x 150 (cross-section 44 mm x 150 mm) is commonly sawn from logs with a top diameter of approximately 180–195 mm. The results in Figure 4 show the share of approved logs within the top diameter intervals for the respective products.

The graph shows, furthermore, that no logs were approved beneath a top diameter of 215 mm. Note that logs approved for production of product 63 x 175 mm are also approved for products with smaller cross-sections, thus also theoretically competing for the same log volume. Twenty-three percent of all logs contained in the Spruce Stem Bank were approved for production of product 44 x 150 mm, 15 percent for 63 x 150 mm and 12 percent for 63 x 175 mm. The graph also shows that more logs can be approved if, for example more sapwood is allowed on the most peripheral third panel, later removing this specific panel from the high content panels (Figure 4, column D).

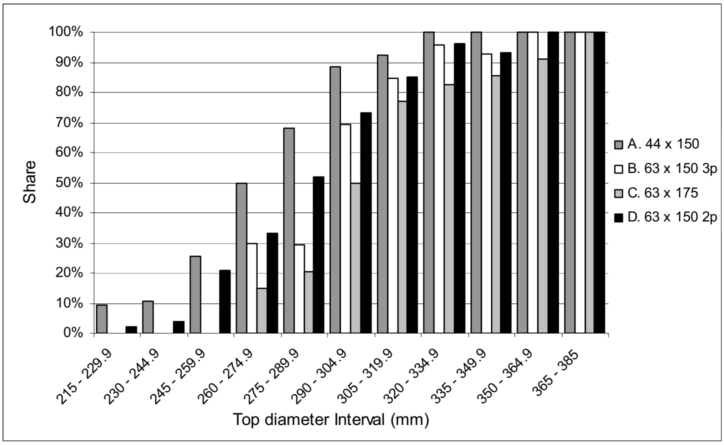

Figure 4. Share of logs approved for production of high-heartwood-content panels within stated top diameter interval. Present scenario required that approved logs should produce two center boards at full log length, allowing a limited share of sapwood. A minimum of 4 mm heartwood on the final panel boards side edge was required. Definitions in Figure 4: 3p = heartwood center boards are split into three panels after drying. 2p = heartwood center boards are split into three panels after drying from which only the two panels closest to the pith show approved heartwood content and are further refined. The concept presented in column D could be an alternate method for increasing the number of approved logs for a specific product.

Figures 5–7 show a comparison of the impact on simulated volume yield for respective breakdown strategies and products (44 x 150, 63 x 150 and 63 x 175)**.**

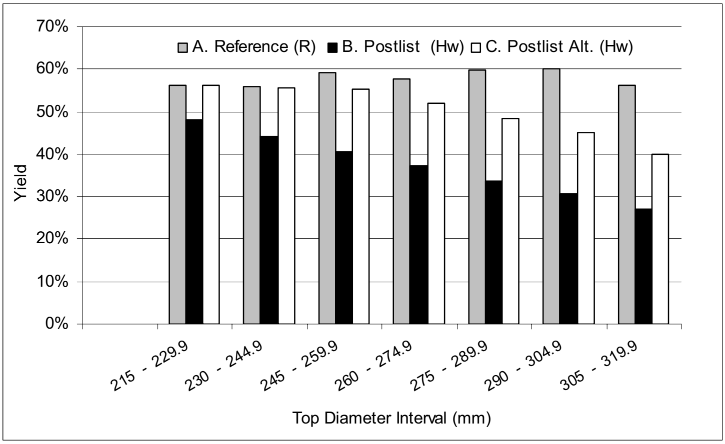

Figure 5. Comparison between three breakdown strategies for product <u>44 x 150</u> and achieved simulated volume yield. "Reference (R)" is a simulated reference value achieved during normal production. "Postlist (Hw)" specifies the simulated volume yield achieved in the heartwood scenario using the basic sawing pattern. "Postlist Alt (Hw)" specifies the simulated volume yield achieved in the heartwood scenario using an alternate sawing pattern with added side boards.

The results show that individual products must be extracted from the most favorable top diameter groups in order to minimize losses. The simulated volume yield generally decreases when high-heartwood-content boards are produced, since the boards are extracted from logs with a larger top diameter in comparison to regular breakdown procedures (Figures 5–7, column B). At best, initial simulation results indicated unacceptable losses in volume yield of 4.5–30 percent points, depending on product and diameter group. For example, when applying the heartwood sawing pattern to logs in the 215–230-mm top diameter interval, volume yield decreased by 8.2 percent point in comparison to the reference value for product 44 x 150 and by 11.7 percent points in the 230–245 interval. However, simulation results from step 4 indicate that volume yield losses could be reduced by adding more side boards to the sawing pattern, in effect also producing side boards with larger widths.

This side-board approach means, for example, that product 44 x 150 can favorably be sawn from approved logs with a top diameter of 215–245 mm, minimizing the loss of yield by extracting more side boards (Figure 5, column C). The basic sawing pattern included two center boards and potentially 2–4 side boards per log (Figure 2, scenario b). The alternate sawing patterns included additional side boards, producing up to 10 side boards per log (Figure 2, scenario c). Extraction of this product from the 245–260 mm interval would result in a loss of 3.8 percent points. Product 63 x 150 is preferably extracted from the 260–275-mm group (Figure 6), but consequently also competes for the same log volume as the 63 x 175 product (Figure 7). The latter product can, however, be extracted from the 275–290-mm group with relatively small losses of 0.8 percent points.

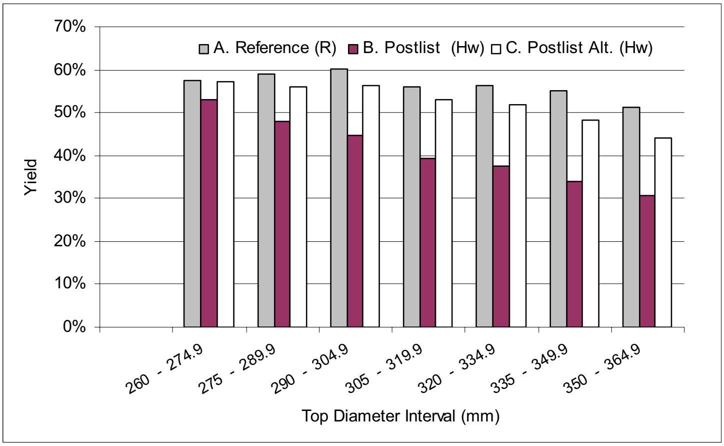

Figure 6. Comparison between three breakdown strategies for product 63 x 150 and achieved simulated volume yield. "Reference (R)" is a simulated reference value achieved during normal production. "Postlist (Hw)" specifies the simulated volume yield achieved in the heartwood scenario using the basic sawing pattern. "Postlist Alt (Hw)" specifies the simulated volume yield achieved in the heartwood scenario using an alternate sawing pattern with added side boards.

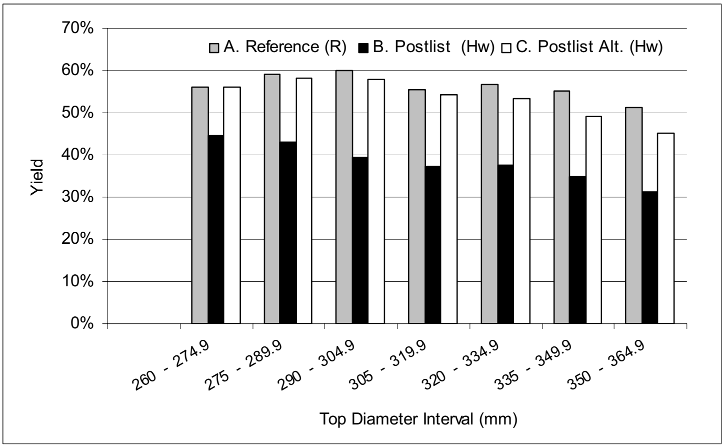

Figure 7. Comparison between three breakdown strategies for product 63 x 175 and achieved simulated volume yield. "Reference (R)" is a simulated reference value achieved during normal production. "Postlist (Hw)" specifies the simulated volume yield achieved in the heartwood scenario using the basic sawing pattern. "Postlist Alt (Hw)" specifies the simulated volume yield achieved in the heartwood scenario using an alternate sawing pattern with added side boards.

Figure 8 shows the total volume yield of heartwood center-boards achieved from approved logs in the most favorable top diameter interval. The heartwood top-diameter share varied between 63% and 84% on all approved logs and between 70% and 84% on logs in favorable log diameter intervals.

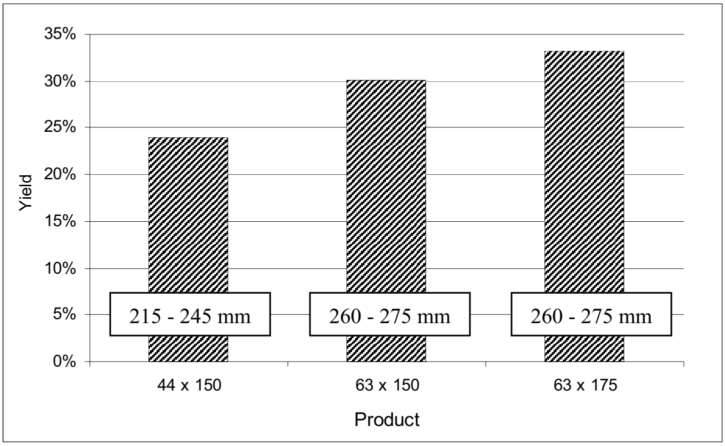

Figure 8. Total volume yield calculated on heartwood center-board volume extracted from approved logs within given top diameter interval.

Discussion and Conclusions

This study shows that an effective and profitable production of high-heartwood-content products is possible. A fundamental issue is to effectively select the most appropriate logs, for example by utilizing industrial x-ray technique. This type of specialized production will also require changes in sawmill strategies, product pricing and measures in order to compensate for loss of yield.

The focus in the present study was set on evaluating a method in which logs best suited for the purpose were broken down under optimized conditions rather than sorting out solitary high-heartwood-content boards in regular production. The three main challenges in production of high-heartwood-content products are to find the most appropriate logs, take measures to compensate for yield losses caused by changed production strategies and to find sufficient log volumes.

An increased production of high-heartwood-content products also entails competition with regular products, since the total available volume of logs is generally limited. Furthermore, products are competing for the same log volume, since simulation results show that they are preferably extracted from adjacent top-diameter intervals. This study shows that high-heartwood product must be extracted from logs with a larger top diameter in comparison to regular production, and these groups of logs are an even more limited asset. Consequently, this specific production strategy requires comprehensive strategic decisions in order to satisfy customer demand for sawn products and simultaneously maximize sawmill profit.

Measures are needed to select appropriate logs and compensate for losses in volume yield. Present methods commonly used for sorting logs in Swedish sawmills by measurements of log geometry and ocular inspection are sufficient to determinate top diameter, log volume, ovality, taper, crook and surface damage. However, a log's inner structure, containing information about heartwood share, knots and defects, is very difficult to determine by using only these methods. Primarily, improved quality sorting methods, *i.e.*, industrial x-ray equipment, must be applied in order to sort out the best-suited logs for the purpose.

It is also shown that the number of approved logs is limited. The top-diameter interval for favorable production of product 63 x 175 contains only 6 logs. This may affect the results presented in the study. One further conclusion could be that, given that the ESSB reflects the forestry supply, the specific product 63 x 175 is not suitable for heartwood products since it requires bulky logs with a very limited supply.

However, there is a potential to increase the number of approved logs by modifying rules governing the selection of appropriate logs.. The products discussed in this study could be extracted from thinner logs if more sapwood is allowed on peripheral parts of the center boards, and the undesirable peripheral panels are screened out later after splitting. Furthermore, the approved board length could be allowed to be shorter than the original log length. This would place demands on the equipment in the green sorting area in order to be able to sort out panels with too high sapwood content and to cut low-heartwood parts from the center boards.

The consequence would also be, apart from loss of yield, that the extracted volume would not increase at the same rate as the increased volume of approved logs. Even more logs could be approved by allowing a higher loss of volume yield.

The yield loss for scenario b, *Postlist (Hw)*, is high in comparison to regular production (Figures 5–7). It can be judged that scenario c, *Postlist alt (Hw)*, is more realistic, since scenario b would not be used in reality. It must also be pointed out that the yield loss will only take place for the approved (selected) logs. Logs not approved and sorted out during the first procedure would in practice be cut according to the sawmill's normal sawing procedure (scenario a, Figure 2).

Results show that effective production of high-content-heartwood products is possible but requires measures to compensate for loss of yield due to the fact that the log top diameter must be increased in comparison to regular production. Pinto *et al.* (2005) showed that log yields of heartwood products could attain between 13% and 16% of log volume, depending on the evaluated case. The higher volume yields achieved in the present study can be explained by the fact that products where extracted from logs particularly selected for the purpose. This conclusion is also supported by Pinto *et al.* (2005), who claim that log selection will produce the highest potential yield. Furthermore, differences in achieved yields in the present results can be explained by deactivated knot definitions, breakdown performed with different sawing patterns and fewer sawing cuts in used sawing patterns.

This study has evaluated the measure of adding more side boards to the sawing pattern. The results indicated that this could reduce the loss of volume yield to a minimum by production of more side boards. However, the sawmill must be able to sell these side boards and panels at full price, compensating for losses in yield and regular production output.

The main problem in this scenario would arise in increased handling and costs caused by the high number of side boards, in some cases up to 10 side boards per log, in the green sorting area, drying kilns and the trimming area. These costs must be compensated when setting the final price on the high-heartwood-content products. One possible way of dealing with the high number of side boards could be to add more center boards to the sawing pattern instead of side boards. This would reduce the number of boards, the handling costs and also the number of sawing cuts.

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