

Predicting Vertical Heartwood Diameter Profiles of Scots pine (*Pinus sylvestris* L.) Based on Data from the Forest

Per Otto Flæte

Norwegian Forest and Landscape Institute
PO Box 115, NO-1431 Ås, Norway

Kjell Vadla

Norwegian Forest and Landscape Institute
PO Box 115, NO-1431 Ås, Norway

Abstract

Concern about environmental impacts of chemical wood preservatives has resulted in increased interest for natural wood durability. The natural durability of sapwood of most species is generally low, while heartwood can be more resistant to biodeterioration. For the sawmill industry various lumber products require certain diameters and lengths of the logs in addition to requirements for wood properties. When utilising the heartwood, it is therefore important to acquire information already in the forest about which trees that can be suitable for logs with a predefined heartwood diameter and length.

The main objectives of this work was to study the variation in heartwood diameter along the stem of Scots pines (*Pinus sylvestris* L.), and to develop a model for predicting heartwood diameter profiles based on variables that can easily be measured in the forest.

Variation in heartwood diameter along the stem was studied in 56 Scots pines sampled from northern parts of Norway. Heartwood diameter decreased from the base and upwards the stem in 49 of the trees. Seven trees deviated from this general pattern. In these trees the heartwood diameter increased from the base of the stem to a maximum at approximately 1-3 m, and then decreased towards the top.

The model developed for predicting heartwood diameter profiles described 86 % of the variation of heartwood diameter. The model was based on the diameter of the actual cross section as the only input variable. This variable can be acquired by a harvester during logging or during field inventories performed by terrestrial laser scanning.

Keywords:

Scots pine, *pinus sylvestris*, heartwood, durability, mixed models, prediction

Introduction

The use of traditional preservative treated wood has been highly restricted in recent years, and there is a need to find environmental benign alternatives. Presently, a lot of effort is put into developing wood protection methods that are ecologically sound and have sufficient efficacy at a reasonable cost. According to Alfredsen (2005) it is not very realistic to develop a multipurpose and environmental benign treatment at a low production cost, which indicates that future use of wood has to be more differentiated according to risk of decay in various environments.

Parallel to the work concerning new methods for wood protection there has been increasing interest in utilising the natural durability of wood for above ground applications. Presently, above ground testing of durability of domestic Norwegian wood species is in progress to establish better knowledge of their potential range of use (Flæte *et al.* 2006). In several European countries special attention is being paid to utilising heartwood of Scots pine. This is probably due to several factors. Scots pine is together with Norway spruce (*Picea abies* (L.) Karst.) the dominating commercial wood species in Norway. The heartwood is moderately durable, and use of Scots pine for exterior applications in buildings has very long traditions.

Heartwood is defined as “the inner layers of the 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 substance” (IAWA 1964).

Formation of heartwood in pine species includes disappearance of stored starch in ray parenchyma cells (Frey-Wyssling & Bosshard 1959), decrease of moisture content (Vintila 1939), closure of pits (pit aspiration) and lignification and death of parenchyma cells (Bauch *et al.* 1974), and deposition of extractives (Bergström 2003).

Heartwood formation in trees has attracted the focus of many scientists, and numerous investigations have been carried out to throw light on this phenomenon. Many of these are summarised by Bamber & Fukazawa (1985), Hillis (1987), and recently by Taylor *et al.* (2002).

Usually, scientists have reported the heartwood in relative units, e.g. heartwood as a proportion of the diameter, proportion of the cross sectional area or of the volume of a tree. This is probably useful when studying the heartwood formation process from a biological point of view and also for the pulpwood industry. Trees with different sizes and ages can be compared. On the contrary, the sawmill industry is highly focused on dimensions in absolute values. A certain sawnwood product often requires logs with a certain diameter and length.

Scots pine belongs to a group of tree species which form regular heartwood. In these species the periphery of the heartwood is similar in shape to that of the outside of the stem. However, the heartwood can have an undulatory outline, which does not correspond to the growth rings. In Scots pine the heartwood periphery may be irregular in shape at the base but regular in the stem (Hillis 1987). If the heartwood has a shape

similar to that of the outside of the stem the heartwood diameter can potentially be modelled by variables describing the outer profile of a tree

The objectives of the present study was to study vertical heartwood diameter profiles in Scots pines sampled from northern parts of Norway and to develop a model for predicting heartwood diameter along pine stems.

Material and Methods

The material used in this study was sampled from seven different locations (low-productivity sites) north of the Arctic Circle in Norway. Eight trees among the dominant and co-dominant trees were randomly selected at each location. The trees were felled and stem discs were extracted from six vertical positions in each tree; at the base, at breast height (1.3 m above ground) and at 20 %, 40 %, 60 % and 80 % of the tree height.

The cambial age of each stem disc was recorded by counting the number of annual rings from bark to pith. Cambial age at breast height ranged from 48 to 204 years. Maximum and minimum diameter under bark and the corresponding heartwood diameters were measured in mm on each stem disc. The mean value of the two measurements was used in the data analyses. Determination of heartwood-sapwood boundary was performed by visual evaluation of colour differences between the two wood types. Characteristics of the sampled trees are listed in Table 1.

Table 1. Characteristics of the sampled trees from each location. TA: Tree age, TH: Tree height, DBH: Diameter under bark at breast height, HWD: Heartwood diameter, bh: breast height (1.3 m)

Stand	Trees N	Location	TA, bh (years)		TH (m)		DBH (mm)		HWD, bh (mm)	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	8	Pasvik	115	6	13.8	1.7	215	13	136	25
2	8	Alta	55	2	11.7	0.7	194	9	104	12
3	8	Kvænangen	55	3	12.3	1.5	205	23	103	18
4	8	Nordreisa	64	9	14.7	1.4	226	26	125	31
5	8	Målselv	127	4	15.5	0.5	252	18	150	26
6	8	Skånland	93	52	10.2	1.3	241	45	130	54
7	8	Saltdalen	81	9	15.4	1.6	253	20	146	15
All	56		84	33	13.4	2.3	227	32	128	33

To model variation of heartwood diameter a mixed linear model using diameter under bark as fixed effect and individual trees as random effect was developed. The model was calculated using the Restricted Maximum Likelihood (REML) method in the Fit Model

platform of the JMP version 6.0.0 software from SAS Institute (2000), following Littell *et al.* (1996).

Root Mean Square Error (RMSE) and adjusted coefficient of determination (R^2_{adj}) were calculated based on simple linear regression between the predicted heartwood diameter values from the mixed model and the measured heartwood diameter values.

Results

In 49 of the 56 studied trees the heartwood diameter decreased with increasing height in the trees. The diameter profiles and heartwood diameter profiles for a 56 year old and 107 year old tree with approximately same diameter at breast height are shown in Figure 1. In the seven remaining trees the heartwood diameter increased upwards from the base and then decreased towards the upper part of the stems. These trees had a cambial age at breast height ranging from 55 to 58 years. In three of these trees the maximum heartwood diameter was found at breast height (1.3 m) while for the other four trees maximum heartwood diameter was found in the stem disc extracted at 20 % of tree height (2.4-2.9 m from the base).

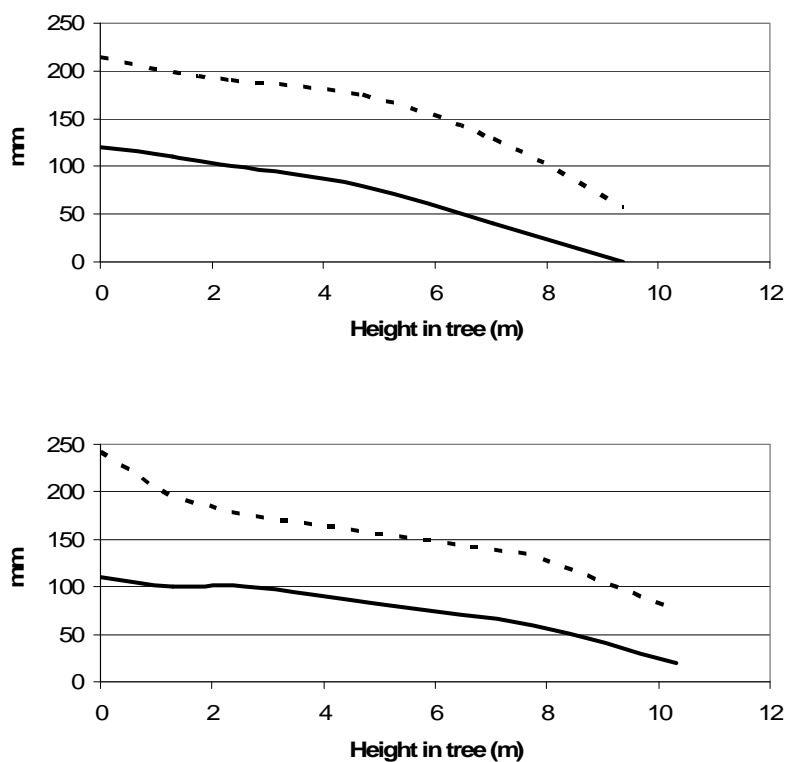


Figure 1. Diameter (dotted line) and heartwood diameter (solid line) for a 56 year old tree (at the top) and a 107 year old tree (bottom).

In 11 of the trees no heartwood was detected in the upper stem disc (80 % of tree height) and in two of these trees there were even no heartwood in the stem disc at 60 % of tree height. The cambial age of the stem discs with no heartwood ranged from 13 to 47 years. Among the 45 trees with heartwood in the upper stem disc the lowest cambial age was 12 years.

The developed model is given in Equation (1)

$$\text{Heartwood diameter (mm)} = -31.4 + 0.684 * \text{Diameter under bark (mm)} \quad (1)$$

The model described 86 % of the variation of heartwood diameter ($R^2_{\text{adj}} = 0.86$). RMSE was 16.9 mm. A plot of predicted versus measured heartwood diameter is shown in Figure 2.

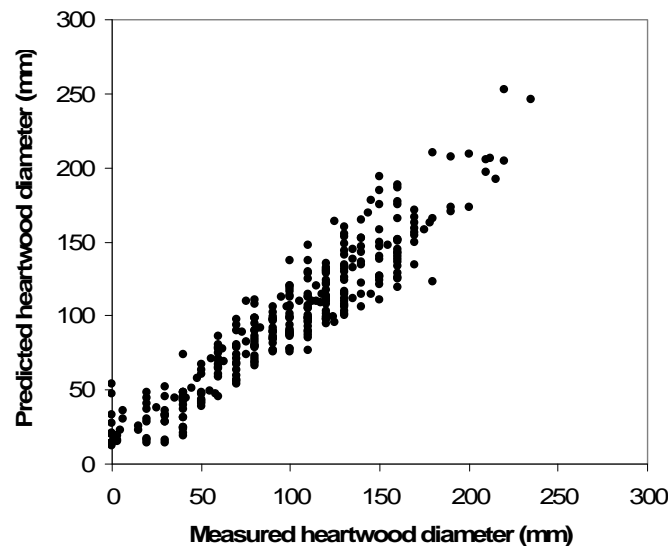


Figure 2. Plot of heartwood diameter predicted by the model versus measured heartwood diameter, $n = 336$.

When interpreting the residuals there was a tendency towards increased residual variance with increasing heartwood diameter. By excluding the data from the discs cut from the base of each stem and recalculating the model this tendency disappeared. The prediction error (RMSE) was slightly reduced to 16.1 mm.

Discussion

The general pattern of heartwood diameter in individual stems showed a decrease with increasing height in tree. This conforms to the results reported by Björklund (1999) who

studied heartwood percentage, heartwood radius and sapwood width in 198 computer tomography (CT) scanned Scots pine stems from 33 stands having an age between 70 and 153 years.

However, in seven of the 56 studied trees the heartwood diameter increased upwards from the base to the stem disc extracted from breast height or at 20 % of tree height, and then decreased towards the upper part of the stems. Because the heartwood diameter was measured on the stem discs it was not possible to determine the exact vertical position where the heartwood diameter reached its maximum. This pattern was only found among the youngest trees. One possible explanation can be that the heartwood formation has been initiated at a lower cambial age in these stem sections than at the base.

Several studies in Sweden have indicated that heartwood formation in Scots pine starts at a cambial age of about 15 years (Fries & Ericsson 1998, Mörling & Valinger 1999, Björklund 1999). The results from the present study showed that the cambial age when heartwood formation is initiated can vary in the upper part of Scots pine trees. Stem discs containing up to 47 annual rings contained no heartwood while heartwood was detected in stem discs with cambial age as low as 12 years.

The model developed for predicting heartwood diameter at various heights in trees based on diameter as the only input variable described a high proportion of the variation of heartwood diameter. Wilhelmsson *et al.* (2002) developed a similar model for Scots pine based on 120 trees originating from 20 pine-dominated stands in Sweden. The age of the trees ranged from 19 to 130 years. The model was also based solely on diameter under bark of the actual cross-section ($R^2 = 0.88$, RMSE = 16.9). The authors recommended, in order to avoid biases in heartwood predictions for very fast- or slow-growing trees, a model based on diameter under bark and the number of annual rings in the actual cross section as input variables ($R^2 = 0.92$, RMSE = 14.1 mm).

A potential application of the presented model can be to integrate it in bucking systems of harvesters. Harvesters measure the diameter continuously along a stem and use the diameter profile when optimising the bucking.

Another application can be in forest inventories. Traditionally, field inventories has been performed by measuring data on standing trees, like diameter at breast height, tree height, crown variables etc. In this perspective it is obviously impractical to measure diameters along the stem of a standing tree. However, in recent years terrestrial laser scanners have been studied as a potential technology to collect field inventory data (e.g. Aschoff *et al.* 2004). It is possible to measure diameter profiles with high precision with this equipment.

It is recommended to validate the model on an independent test set to evaluate the predictive ability. It can also be an alternative to develop models for mature and young trees separately.

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