Identifying Heartwood-rich Stands or Stems of *Pinus sylvestris* by Using Inventory Data

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Variations in heartwood percentage, heartwood radius and sapwood width, within and between stands of Scots pine (*Pinus sylvestris* L.), were analysed using a database of 198 CT-scanned (computer tomography) stems from 33 research plots (stands) throughout Sweden. Heartwood percentage varied greatly both between individual trees and between stands, and correlated poorly to site, stand and tree variables. This implies that it seems unfeasible to identify heartwood-rich stands or stems, e.g., for production of heartwood products, by using inventory data. Heartwood formation expressed as the number of new heartwood rings formed each year was found to increase with increasing cambial age, from about 0.5 rings per year at a cambial age of 45 years, to about 0.8 rings per year at a cambial age of 115 years.

Keywords heartwood, *Pinus sylvestris*, sapwood, wood utilisation

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1 Introduction

Many wood properties including heartwood percentage influence the utilisation of Scots pine (*Pinus sylvestris* L.). Heartwood differs from sapwood in properties such as colour, natural durability, and suitability for chemical treatment (Panshin and de Zeeuw 1980, Haygreen and Bowyer 1989). These are important properties for many products. New scanning techniques today make it possible to determine heartwood percentage of logs on line in sawmills (Grönlund and Grundberg 1997). This means that it will be possible to determine sawing patterns that optimise the output of heartwood products from an individual log. For example, the heartwood of *Pinus canariensis* has been used for carpentry products for a long time (Climent et al. 1993), and Rydell (1992) assumed that a similar development could take place concerning the utilisation of heartwood from Scots pine in Sweden. However, the economic feasibility of such production systems depends on many factors including our ability to identify stems or stands with high heartwood percentage.

Heartwood formation in Scots pine has been found to start at the age of 30–40 years in Finland (Lappi-Seppälä 1952), and at the age of 30–35 years in Germany (Pilz 1907, Kuhn 1918), whereas some recent studies in Sweden indicate a starting (cambial) age well below 25 years (Fries and Ericsson 1998, Mörling and Valinger 1998) . For many species there is also a narrow transition zone surrounding the heartwood that contains living cells, but has a moisture content similar to heartwood (Hillis 1987). The width of the transition zone in Scots pine is not known but it can, judged from other species, be assumed to be one to two growth rings wide. The heartwood-sapwood ratio in conifers has been extensively studied and the subject was reviewed by Bamber and Fukazawa (1985). To focus on the heartwood may be most relevant from a wood utilisation perspective, whereas from a physiological point of view it may be more relevant to focus on the sapwood. Sapwood carries water and nutrients from the roots of the tree to the needles. Correlations between sapwood width and some tree characteristics can therefore be expected to be stronger than corresponding correlations to heartwood diameter. Many studies have also focussed on sapwood content (e.g. Yang et al. 1985, Yang and Murchison 1992, Sellin 1993, 1996). Many authors have found that heartwood diameter of Scots pine is relatively constant up to about 20 % of the tree height, after which it tapers off towards the top of the tree (Nylinder 1961, Tamminen 1962). This means that because of stem tapering and butt swelling, heartwood percentage increases up to about 20 % of the tree height. Average sapwood width has been found to differ between softwood species, but to be relatively constant along the trunk of individual trees (Yang et al. 1985, Yang and Murchison 1992).

One theory for the heartwood-sapwood ratio that is often referred to is the so-called “pipe model” which states there is a constant ratio of foliage mass to sapwood cross-sectional area at crown base (Shinozaki et al. 1964). This implies that for trees of similar stem size, heartwood percentage should be lower for trees with bigger crowns. It should then be possible to explain the variation in heartwood percentage by describing the size of the crown. Many authors have reported results supporting this general model. Nylinder (1961) found that heartwood percentage of Scots pine decreased with increasing length of the live crown and with increasing width of the last ten growth rings. Sellin (1993) found in a study on *Picea abies* that the sapwood can be considerably wider for dominant trees than for suppressed trees. He later concluded (Sellin 1996) that the higher the growth rate, the larger the sapwood zone. However, somewhat contradictory to these findings are those of Leibundgut (1983) which indicated that fast-growing trees at low altitudes had higher heartwood percentage than slow-growing trees at high altitudes. Another tree characteristic presumably linked to vigour is crown defoliation caused by air pollution. Steffen et al. (1990) investigated wood properties of Scots pine trees with varying degree of crown defoliation from four locations in Sweden, but could not find any significant correlations to heartwood percentage.

Another theory is that heartwood formation proceeds with a constant fraction of a growth ring for each new ring formed by the cambium. Wilkes (1991) investigated *Pinus radiata* and found evidence for this theory. Heartwood production then becomes greater where rings are wider, and vigour per se should have little or no influence on heartwood formation. Wilkes argued that this could explain the sometimes contradictory results of other investigations. This theory is supported partly by the finding that heartwood content correlates to the early growth rate of the tree. Climent et al. (1993) found a positive correlation between heartwood radius of *Pinus canariensis* and radius to the 25th ring. Hillis and Ditchburne (1974) concluded that a knowledge of stem diameter at five years of age improved the prediction of heartwood diameter in 20–50-year-old *Pinus radiata*. Hazenberg and Yang (1991) studied the expansion of sapwood and heartwood in *Picea mariana* as a function of time. They found that the heartwood expanded at an average rate of 0.81 ring per year from 10 to 90 years, after which it was close to one ring per year.

The variation in heartwood percentage between trees and stands of Scots pine is often considerable. Tamminen (1962) investigated 20 stands in Sweden and recorded a coefficient of variation between stands of 15 %, whereas Björklund and Walfridsson (1993) in a study comprising 29 stands in Sweden recorded about 25 % variation, both between stands and between stems within a stand. Several authors have found age, or the logarithm of age, to be the best independent variable for explaining the variation in heartwood percentage in Scots pine. Uusvaara (1974) studied plantation-grown Scots pine in the age interval 20–80 years and found that age caused 37 % of the variation. In the study of Björklund and Walfridsson (1993) age ranged from 42 to 192 years and this variable accounted for about 40 % of the variation in heartwood percentage. They also tested various other independent variables, but concluded that these added little to the explanation. Sellin (1996) found that tree age and growth rate together described 70 % of the variation in sapwood content for *Picea abies* in Estonia. Predicting heartwood width has proved to be easier than predicting heartwood percentage. Climent et al. (1993) found that a function of cambial age and radius to the 25th ring accounted for 91 % of the heartwood width variation in *Pinus canariensis.*

The big variations in heartwood percentage recorded in many studies has drawn the interest of geneticists. Fries and Ericsson (1998) found a high heritability for heartwood diameter in a study on 25-year-old full-sibs of Scots pine in northern Sweden, and they concluded after one more study on 44-year-old Scots pine that the heritability was remarkably high (Ericsson and Fries 1998).

Although much is known about correlations between heartwood content and growth factors, there is less information on correlations to site characteristics, and on the variations under different conditions. Furthermore, it is still unclear whether heartwood formation, in terms of growth rings per year, is determined by growth factors or if it proceeds with a constant fraction of the increment each year. Thus there is still a lack of predictive models for heartwood content variations in Scots pine that could be used for selection of heartwood-rich stems or stands, and for production planning purposes. Finally, parallel analyses of heartwood percentage, heartwood radius and sapwood width may improve our understanding of what causes the variations in heartwood content.

The objectives of this study were to determine the magnitude of variations in heartwood content within and between Scots pine stands; to analyse correlations to site, stand and tree variables; and to analyse the number of heartwood rings as a function of cambial age.

2 Material and Methods

The study was based on the “Pine Stem Bank”, a database jointly developed by the Department of Wood Technology of Luleå University, the Swedish Institute for Wood Technology Research and the Department of Forest Management and Products of the Swedish University of Agricultural Sciences (Grönlund et al. 1995, 1996). The database contains information on 198 Scots pine stems from 33 well-documented research plots (stands) in Sweden. The stands were chosen in order to get a wide distribution of latitude, site index, regeneration method, and thinning strategy. The stems in each stand were divided into three DBH-classes: small trees, medium size trees, and big trees (DBH = diameter at breast height, 1.3 m above ground). From each DBH-class two stems with similar DBH were chosen (Table 1). For each tree the whole sawlog length, normally to a top diameter of about 130 mm, was scanned using computer tomography (CT-scanning) for detection of interior properties. Growth ring widths were measured at the butt end of each log along a radius from pith to cambium. The measurements were made on digital photographs using image analysis techniques. The growth ring widths were adjusted to the average distance from pith to cambium, which was derived from the corresponding CT image. Based on measurements at the butt end of the stem, two relative growth ring indices were defined, one for the initial growth ($F20_{rel}$ = average width of first 20 rings divided by the mean ring width) and one for the last period prior to felling ($L10_{rel}$ = width of last 10 rings divided by the mean ring width). These were constructed to reflect the growth pattern of each individual stem and to facilitate comparisons between stems from different site indices. Another indicator of growth,

Table 1. Summarized stand and tree characteristics for the 33 sample plots (stands). Six Scots pine trees from three DBH-classes were sampled from each stand. Figures in brackets are number of stands.

Regeneration method	Planting (10), sowing (9), natural regeneration (14)
Spacing (if planted or sowed)	0.75 m–3 m (including two spacing trials comprising seven stands)
Thinning strategy	Five block-wise comparisons of crown thinning vs thinning from below (5×2). Other stands thinned from below (21) or treated with mixed thinning strategies (2)
Latitude	Approximately 57°–66°N (from south Sweden to north Sweden)
Site index (SI)	16 m–28 m (SI = height of dominant trees at 100 years age)
Stand age	From 70 to 153 years
Tree height (H)	17.5 m to 27.6 m (average of six sample stems per stand)
Diam. at br. height (DBH)	212 mm to 403 mm (average of six sample stems per stand)
DBH (by DBH-class)	Small trees 244 mm , medium size trees 286 mm, big trees 331 mm

and thereby a variable possibly correlated to heartwood content, is the length of the live crown. Also here, a relative value, crown ratio (CR), facilitates comparison between stands. Other tree variables used in the correlation analysis were DBH, height to live crown base (HLC), and tree height (H).

The logs were CT-scanned in fresh condition which, because the scanning records the green density of the material, facilitates an accurate detection of the moisture content border between heartwood and sapwood (Fig. 1). Thus the transition zone was taken as a part of heartwood. This detection was done by using image analysis techniques (Grundberg 1994). CT-scanning was done at 10-mm height intervals and the distances from pith to sapwood and to log surface under bark were determined in 360 directions. The data were reduced to a data-set containing 36 directions at 10-cm height intervals. Heartwood percentage was expressed as area percentage ($HW_{\%}$). The analysis also encompassed heartwood radius (HW_{rad}) and sapwood width (SW_{wid}).

To analyse the variations between stems and stands a single value giving the best possible representation of the whole stem was needed. This value should minimize or control for example the effects of butt swelling and stand age. A stem section fulfilling these requirements was selected by describing the vertical variation of $HW_{\%}$, HW_{rad} and SW_{wid} in a sub-sample of stems comprising the youngest stand, the 70-year-old stand planted on site index 24 m, and the oldest stand which was 153 years of age and naturally regenerated on site index 22 m (Fig. 2). These were chosen based on the assumption that age is an important factor for heartwood content.

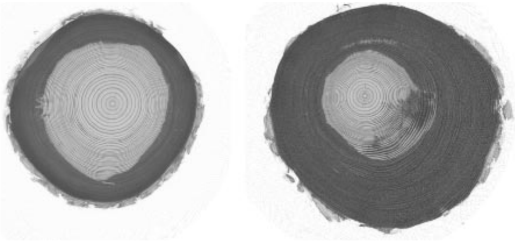

Fig. 1. An illustration of the heartwood percentage variation within stand. Computer tomography images (CT- scanning) from 2 m height of two stems from the same stand.

The variation analyses were done using procedures for mixed models, with stand classified as a random variable and DBH-class classified as a fixed variable. However, for the analysis of the relation between within-stand variation and stand variables (stand age and site index), the six sample trees were considered as randomly sampled. The analysis of within-stand correlations to tree variables was made using a method based on linear regression. Stand (1, 2,....33) was used as class variable and the increase in the adjusted coefficient of determination (R^2adj) when tree variables were entered into the model was calculated. The analysis of stand level correlations to site, stand, and tree variables was based on arithmetic mean values for the six stems from each stand and linear regressions.

The investigated parts of the stems were crosscut into two to four logs depending on length, and growth rings were measured at the butt ends of these logs. Cambial age and the number of heartwood rings could thereby be estimated at different heights in the stems, ranging from stump level to 15 m height, thus providing a possibility to analyse heartwood formation as a function of cambial age. The slope of a regression line indicates the number of heartwood rings that are formed each year.

All statistical analyses were conducted by using standard procedures, such as General Linear Models, Regression, and Mixed Models, of the Statistical Analysis System (SAS) version 6.12 (SAS Institute 1989).

Table 2. Descriptive statistics and variation analysis for heartwood percentage ($HW_{\%}$), heartwood radius (HW_{rad}) and sapwood width (SW_{wid}), at 3.5–4.5 m height. 198 stems divided on 2 stems per DBH-class and 33 stands.

	Descriptive statistics $HW_{\%}$	 HW_{rad}	 SW_{wid}
Mean value	36 %	69 mm	46 mm
Min-max, stems	12–63 %	31–119 mm	22–90 mm
Min-max, stands	26–46 %	46–105 mm	34–68 mm

Source of variation	Coefficients of variation $HW_{\%}$	 HW_{rad}	 SW_{wid}
Stand	13.7 %	21.5 %	16.0 %
Stand (DBH-class	5.4 %	6.5 %	7.4 %
Tree within DBH-class	18.0 %	9.9 %	14.6 %

3 Results

The examples chosen to illustrate the vertical variation within stems showed that heartwood radius tapered at a rather constant rate. Sapwood width was biggest at the butt end of the stem, and was rather constant above 3 m height. $HW_{\%}$ increased the first few metres from the butt end of the stem and decreased towards the top of the stem. The decrease began at about 4 m height in the young stand, whereas $HW_{\%}$ in the old stems remained fairly constant up to 10 m height (Fig. 2). The approximately constant $HW_{\%}$ from 4 to 10 m height in the old stand, and the short section at about 4 m height in the young stand showing a similar feature, might indicate that the age-dependent increase in $HW_{\%}$ levels out at a certain cambial age. Comparing different stands at a height where the cambial age is high enough then means that the effect of stand age would be minimized. From these observations it can be concluded that, given the range in stand age in this investigation from 70 to 153 years, a stem section at about 4 m height can serve as a basis for further analysis of variations within and between stands. The following analyses are therefore based on mean values from ten measurement heights ranging from 3.5 to 4.4 m height of each stem.

The three investigated properties, $HW_{\%}$, HW_{rad} and SW_{wid}, showed considerable variations within stands as well as between stands. $HW_{\%}$ variation was higher within DBH-class than between stands. A comparison of the coefficients of variation for HW_{rad} and SW_{wid} also indicates that $HW_{\%}$ variations within DBH-class depend more on differences in sapwood width, whereas $HW_{\%}$ variations between stands depend more on dif-

Table 3. Analysis of the variation among DBH-class levels. 198 stems divided on 2 stems per DBH-class and 33 stands (SE = standard error; Means not significantly different between DBH-classes are followed by the same letter).

DBH-class	Relative DBH	$HW_{\%}$ Mean %	 SE %	HW_{rad} Mean mm	 SE mm	SW_{wid} Mean mm	 SE mm
Small	0.85	34.2a	1.22	57.1a	2.83	40.6a	1.64
Medium	1.00	36.0a	1.23	69.2b	2.83	46.0b	1.65
Big	1.16	36.5a	1.23	79.3c	2.83	52.6c	1.65

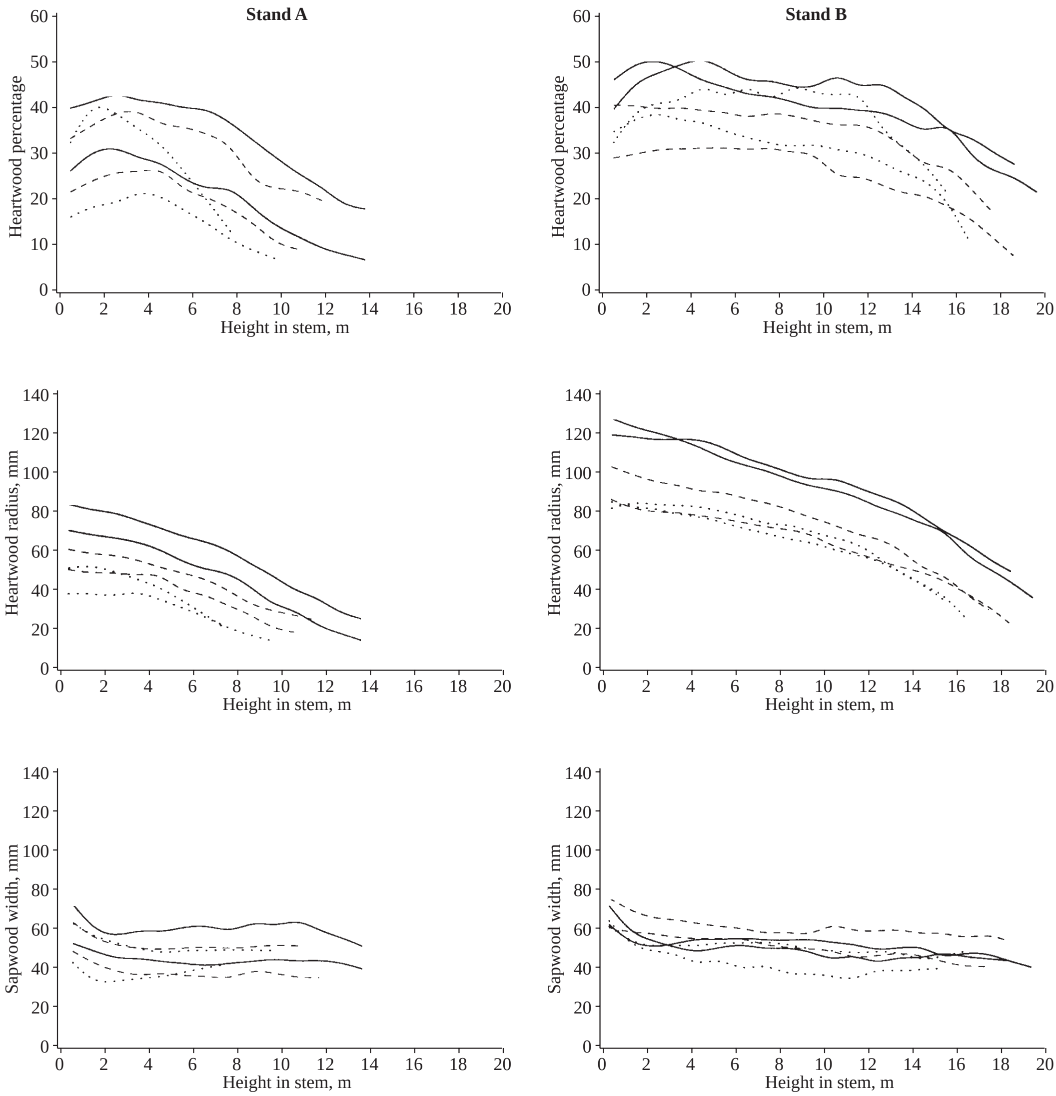

Fig. 2. Heartwood percentage ($HW_{\%}$), heartwood radius (HW_{rad}) and sapwood width (SW_{wid}) in the sawlog section (butt end to about 13 cm diam.) of six stems per stand from two stands. Stand A on site index 24 m and 70 years of age, stand B on site index 22 m and 153 years of age.
Legend: · · · · · · · · = small trees, - - - - - = medium size trees, ——— = big trees.

ferences in heartwood radius. The interaction between stand and DBH-class was relatively small, indicating that the within-stand tree size effect was about the same for the stands (Table 2). $HW_{\%}$ was not significantly different between DBH-classes whereas both HW_{rad} and SW_{wid} increased with increasing tree size (Table 3).

The within-stand variation of $HW_{\%}$, HW_{rad} and SW_{wid}, expressed as coefficient of variation for the six sample trees, showed, with one exception, no correlation to stand age or site index. The exception was HW_{rad} where the variation decreased with increasing site index (Table 4).

The analysis of variations between stems within

Table 4. Multiple regression on the relationship between within-stand variation, expressed as coefficient of variation of heartwood-sapwood properties, and stand age and site index. N = 33. Model form: c.v. of $HW_{\%}$ = f(age, SI).

Property	R^2adj for the model	Variable	Parameter estimate	Standard error	Prob >/T/
c.v. of $HW_{\%}$	0.04	intercept	0.2429	0.1386	0.0898
		age	–0.0005	0.0006	0.4001
		SI	–0.0006	0.0042	0.8981
c.v. of HW_{rad}	0.17	intercept	0.3466	0.1058	0.0027
		age	0.0000	0.0004	0.8755
		SI	–0.0070	0.0032	0.0373
c.v. of SW_{wid}	0.10	intercept	0.1366	0.1189	0.2589
		age	–0.0004	0.0005	0.4509
		SI	0.0036	0.0036	0.3258

Table 5. Regression analysis, within stands, for individual trees of heartwood percentage ($HW_{\%}$), heartwood radius (Hw_{rad}), and sapwood width (Sw_{wid}) on various tree variables (DBH = Diameter at breast height, HLC = Height to live crown base, H = Tree height).

	Increase in R^2adj when tree variable(s) are added to a model where stand is class variable (R^2adj for the model y = stand were 0.46 for $HW_{\%}$, 0.63 for HW_{rad}, and 0.49 for SW_{wid})		
Tree variables	$HW_{\%}$	HW_{rad}	SW_{wid}
DBH (mm)	0.01	0.24	0.23
H (m)	0.00	0.15	0.10
HLC (m)	0.01	0.00	0.00
CR (%)	0.00	0.04	0.05
$F20_{rel}$(%)	0.05	0.00	0.06
$L10_{rel}$(%)	0.03	0.01	0.00
Best combination of tree variables			
HLC + $F20_{rel}$	0.06		
DBH + $F20_{rel}$		0.25	0.26

stands showed that $HW_{\%}$ correlated poorly with the six selected tree variables, with the least poor correlations for the relative growth ring indices ($F20_{rel}$ and $L10_{rel}$). HW_{rad} and SW_{wid} correlated somewhat better with the tree size indicator variables, DBH and H, whereas correlations with crown height, crown ratio, and growth ring indices were close to zero. Multiple regressions gave almost no increase of the adjusted coefficient of determination (Table 5).

The analysis at stand level covered, besides tree variables, some site and stand characteristics (site index, latitude, and stand age). The best variable for explaining the variation in $HW_{\%}$ was the height to live crown (HLC), followed by the crown ratio (CR). Increased HLC and decreased CR correlated with increased $HW_{\%}$. Also, $F20_{rel}$ correlated well with $HW_{\%}$, whereas site index and latitude did not correlate at all. Variables positively correlated to tree size also showed positive correlation to HW_{rad}, whereas corresponding correlations to SW_{wid} were less pronounced (Table 6).

The 33 investigated stands encompassed five studies where low thinning was compared to crown thinning, and two studies on initial spacing. The analysis did not indicate that these silvicultural measures influenced heartwood percentage (Table 7).

The number of heartwood rings as a function of cambial age was best predicted by a second degree polynomial (Fig. 3). The slope of the regression line indicates that heartwood formation proceeds with 0.5 rings per year when cambial age is about 45 years, with 0.7 rings per year when cambial age is about 90 years, and with 0.8 rings per year when cambial age is about 115 years. There was thus a clear tendency that heartwood formation, expressed as the number of new heartwood rings formed each year, increases with increasing cambial age.

Table 6. Regression analysis for stand means of heartwood percentage ($HW_{\%}$), heartwood radius (HW_{rad}) and sapwood width (SW_{wid}) on various site, stand and tree variables. N = 33. (DBH = Diameter at breast height. HLC = Height to live crown base. H = Tree height.)

		$HW_{\%}$ (%)		HW_{rad}(mm)		SW_{wid}(mm)	
		R^2	Regr. coeff.	R^2	Regr. coeff.	R^2	Regr. coeff.
Simple regression							
DBH	mm	0.12	0.036	0.85	0.25	0.64	0.12
H	m	0.26	0.96	0.73	4.33	0.29	1.43
HLC	m	0.41	1.39	0.51	4.18	0.04	n.s.
CR	%	0.37	–0.59	0.09	n.s.	0.09	n.s.
$F20_{rel}$	%	0.33	0.11	0.32	0.29	0.01	n.s.
$L10_{rel}$	%	0.11	n.s.	0.01	n.s.	0.05	n.s.
SI	m	0.02	n.s.	0.14	1.61	0.13	0.79
Age	year	0.13	0.07	0.21	0.25	0.02	n.s.
Lat	deg.	0.00	n.s.	0.15	–2.00	0.29	–1.48

n.s. = not significant at the 5 % level

Table 7. Analysis of the influence of thinning strategy and initial spacing on heartwood percentage.

Material	Thinning strategy		Initial Spacing					
	low	crown	0.75	1.25	1.5	2.0	2.5	3.0
	Average $HW_{\%}$ at 3.5–4.4 m height							
5 thin. trials, SI 16–27 m, 127–143 years	36 %	36 %						
Spacing trial, SI = 28 m, 87 years			35 %	34 %	35 %	–	–	34 %
Spacing trial, SI = 23 m, 77 years			–	–	35 %	38 %	31 %	–

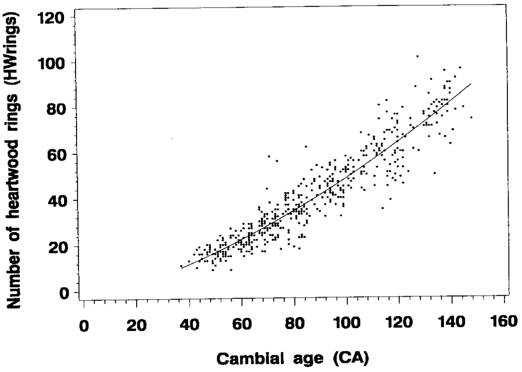

Fig. 3. The number of heartwood rings as a function of cambial age. Height in stem ranging from stump level to 15 m. The fitted model was found to be $HW_{rings} = -4.8297 + 0.3232 \cdot CA + 0.0021 \cdot CA^2$. $R^2 = 0.88$, RMSE = 7.1, n = 503. Both regression coefficients were strongly significant, $p > 0.0001$.

4 Discussion

4.1 Material and Methods

The sample plots used for this study were small and carefully managed, thus not necessarily representative of full-size normally managed stands. This is an important reservation concerning variation estimations of properties such as knottiness where silviculture is known to play a fundamental role, but should be of minor importance for the heartwood-sapwood relation. In this study it is more important that for example site index and stand age are correctly estimated.

To distinguish heartwood from sapwood in a specific sample is seldom a problem and can be accurately done with different methods. However, stems are normally not perfectly cylindrical, the position of the pith is seldom exactly in the centre, and heartwood extension can be different in different directions. This means that many observations are needed in order to accurately determine heartwood or sapwood content of a stem. This has been stressed by e.g., Fries and Ericsson (1998). In the present study the stem level estimates of $HW_{\%}$, HW_{rad} and SW_{wid} were based on 360 observations within a one-metre stem section. The accuracy at stem level should thus be high.

4.2 Results

The present study confirms earlier studies showing that heartwood content varies considerably, both between individual trees and between stands, and correlates poorly with site, stand and tree variables. It was found that the variation between trees within the same DBH-class, growing in the same stand, was higher than the variation between stands. These results indicate that Scots pine in terms of heartwood formation is little affected by where it is grown, and only to a limited extent affected by how it is grown. This conclusion is in accordance with Mörling and Valinger (1998) who found that the effects of thinning and fertilisation on the amount of heartwood, 12 years after treatment, was limited. However, the variation between stands, and the correlation to age, was lower in this study than in the studies of Uusvaara (1974) and Björklund and Walfridsson (1993). This was probably because there were no stands younger than 70 years in this study. Young stands have low heartwood percentage and the variation between stands therefore increases when such stands are included in the investigations.

The finding that the number of new heartwood rings formed each year increases with increasing cambial age corresponds well with a study on *Picea mariana* (Hazenberg and Yang 1991). However, it seems that the fraction of a growth ring yearly transformed from sapwood to heartwood is lower for Scots pine compared to *Picea mariana*. The present study also indicates, although this result was reached by extrapolation, that heartwood formation should start at a cambial age of about 15 years. This is a considerably lower age to that found in earlier studies on Scots pine in Finland and Germany (Pilz 1907, Kuhn 1918, Lappi-Seppälä 1952), but corresponds well with recent studies in Sweden (Fries and Ericsson 1998, Mörling and Valinger 1998).

The relatively strong correlation between cambial age and the number of heartwood rings, and the very low correlations between heartwood content and site, stand and tree variables, can be seen as a support for the theory that heartwood formation proceeds with a constant fraction of a growth ring per year. That the relative width of the first 20 growth rings ($F20_{rel}$) was among the least poor variables for describing heartwood percentage further supports this conclusion. It seems that this process, combined with a normal growth ring pattern of Scots pine in Sweden (thick growth rings close to the pith and thinner growth rings further out), results in a heartwood formation that starts at a cambial age of about 15 years and levels out at about 35 %, some 50 years later. The length of the stem section with 35 % heartwood extends upwards as the tree gets older, and for trees of 130–150 years of age it may reach 8–10 m height (as exemplified by stand B in Fig. 2). The correlation with $F20_{rel}$, although weak, also implies that a silvicultural programme aimed at minimising the knot size (slow growth at the beginning of the rotation period and fast growth at the end) will result in decreased heartwood percentage.

The results of this study imply that it seems unfeasible to identify heartwood-rich stands or stems, e.g., for production of heartwood products, by using inventory data. However, the big variability and the possibility to detect heartwood through scanning techniques, means that scanning and log sorting at the sawmill could be an option worth exploring. A high within-stand variation in heartwood percentage could actually be positive from a utilisation perspective if the logs were scanned for interior properties before sawing. The likelihood of finding some logs with very high heartwood percentage would then increase. However, the results in Table 4 show almost no correlations between within-stand variations and site index or stand age. Thus we can only conclude that the bigger the logs are, the bigger the incentive for thinking in terms of heartwood products. If we want stems richer in heartwood in the future, this will more likely be achieved through genetical breeding than through silviculture and site selection. Fries and Ericsson (1998) concluded in a study on genetic parameters in Scots pine breeding that it should be fruitful to include increased heartwood formation as a goal in breeding programs without counteracting or reducing any progress on production traits.

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