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Heartwood and sapwood development within maritime pine (*Pinus pinaster* Ait.) stems

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Abstract Heartwood and sapwood development in maritime pine (*Pinus pinaster* Ait.) is reported based on 35 trees randomly sampled in four sites in Portugal. It was possible to model the number of heartwood rings with cambial age. The heartwood initiation age was estimated to be 13 years and the rate of sapwood transformation into heartwood was 0.5 and 0.7 rings year⁻¹ for ages below and above 55 years, respectively. Reconstruction of heartwood volume inside the tree stem was made by visual identification by image analysis in longitudinal boards along the sawn surfaces. This volume was integrated into the 3D models of logs and stems developed for this species representing the external shape and internal knots. Heartwood either follows the stem profile or shows a maximum value at 3.8 m in height, on average, while sapwood width is greater at the stem base and after 3 m remains almost constant up the stem. Up to 50% of tree height heartwood represents 17% of stem volume, in 83-year-old trees and 12–13% in 42 to 55-year-old trees. Tree variables such as stem diameter, DBH and tree total height were found to correlate significantly with the heartwood content.

Keywords *Pinus pinaster* Ait. · Maritime pine · Heartwood · Sapwood · Growth rings

Introduction

The xylem of most tree species contains two histologically similar but physiologically different zones: the sapwood and the heartwood. The sapwood, the outer zone, contains physiologically active living cells and

reserve materials. The outer rings allow the transport of water and minerals from the roots to the cambium and leaves.

The heartwood, the inner zone of the xylem, is physiologically inactive regarding water conduction. With tree ageing, the parenchyma cells die, lose their reserve material and the wood becomes impregnated with complex organic compounds. These are normally referred to as extractives and are responsible for the natural durability of this xylem zone and for its usually darker colour.

The mechanisms underlying these changes and the physiological functions of heartwood are not yet well known. It has been suggested that heartwood formation serves to regulate the amount of sapwood to a physiological optimum level (Bamber 1976), following the “pipe-model” theory relating sapwood area to foliage mass (Shinozaki et al. 1964). The amounts of heartwood and sapwood should therefore be related to all factors and conditions that affect crown size and vitality (Mörling and Valinger 1999; Bergstrom 2000). Other studies support that, after a certain initiation phase, heartwood is formed at a constant annual ring rate. Consequently, heartwood would be related to the cambial age and to the factors that impact growth rates, mainly in early stages (Hazenberg and Yang 1991; Wilkes 1991; Climent et al. 1993, 2002; Sellin 1994; Bjorklung 1999; Gjerdrum 2002).

Heartwood and sapwood contents vary between and within species and have been related to growth rates, stand and individual tree biometric features, site conditions and genetic control. Reviews on heartwood and sapwood formation and variation can be found in Bamber and Fukazawa (1985), Hillis (1987) and Taylor et al. (2002).

Heartwood and sapwood have different properties and their proportion within the tree will have a significant impact on the utilisation of wood. For pulping, heartwood is at a disadvantage as its extractives can affect the process and product properties. For solid wood applications the different properties of heartwood and sapwood influence drying, durability, and aesthetic values for the consumer (panels and furniture). When there is a large

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colour difference between sapwood and heartwood, selection of wood components by colour also plays a significant role in some timber applications. This is the case for maritime pine (*Pinus pinaster* Ait.) where heartwood shows a strong reddish colour.

Maritime pine spreads naturally in Atlantic-influenced regions of Portugal, Spain and France (subspecies *atlantica*) and in the Mediterranean regions of France (including Corsica), Spain and Italy (including Sardinia and Sicily) (subspecies *pinaster*). In recent decades this species has been introduced with success into South Africa, New Zealand and Australia. In southern Europe it occupies approximately 4 million ha and in Portugal it is the most important species accounting for about 30% of the total forest area.

Maritime pine wood has pale yellow sapwood and reddish-brown heartwood. The heartwood is distinct with clearly defined growth rings and is naturally durable (Carvalho 1997; Cruz and Machado 1998). Very few studies have been presented in the literature concerning heartwood and sapwood development in this species. In 75-year-old maritime pine trees, heartwood represented 44% of the diameter at breast height and contained three times more extractives than sapwood (Esteves 2000). Stokes and Berthier (2000) and Berthier et al. (2001) studied the heartwood irregularity in relation to reaction wood in lean trees and found more heartwood rings on the leaning side of the tree, while Ezquerria and Gil (2001) reported on heartwood anatomy and stress distribution in the stem.

This paper aims to study the heartwood and sapwood formation and development in maritime pine, using ring analysis and a three-dimensional reconstruction algorithm

of heartwood that was added to the virtual stem representation already developed for this species (Pinto et al. 2003). The virtual stems thus obtained allowed us to study the cross-sectional and axial development of heartwood and sapwood within the tree.

Materials and methods

The study was based on 35 maritime pine (*Pinus pinaster* Ait.) trees sampled from different sites in Portugal. Heartwood was identified visually by image analysis in longitudinal boards along the sawn surfaces. Reconstruction of heartwood volume inside a log/stem was made and integrated with the 3D models of logs and stems developed for this species representing the external shape and internal knots (Pinto et al. 2003). Growth ring widths were measured at different stem levels.

Sampling

Thirty-five maritime pine trees were sampled from four stands in Portugal, covering the species' area of distribution and different management types: 20 trees in Leiria (S1), 5 trees in Mação (S2), 5 trees in Alpiarça (S3) and 5 trees in Marco de Canavezes (S4). The Leiria pine forest (S1) is state-owned with management oriented to produce high quality wood including pruning before the first thinning, 5-year rotation thinning between 20 and 40 years of age, and clear cutting at an age of approximately 80 (Gomes 1999). The other sites (S2–S4) are private-owned uneven aged stands, without cultural operations and trees are harvested within 40–50 years.

The trees were randomly sampled within each site. Total height, crown height and height of the first visible dry branch were measured for each tree. Two cross diameters (N-S, W-E) were measured every 2.5 m along the tree and the bark thickness was determined with a bark gauge at the point of greatest thickness. Table 1 shows the location and main geographic and climatic

Table 1 Site characterisation

Stand	S1	S2	S3	S4
Coordinates ^a	08°55'55"W, 39°45'02"N	07°59'49"W, 39°33'14"N	08°35'05"W, 39°15'36"N	08°08'55"W, 41°11'08"N
Altitude (m, a.s.l.)	88	278	25	216
Mean air temperature (°C)	12.5–15.0	15.0–16.0	16.0–17.5	12.5–15.0
Relative air humidity (%)	80–85	75–80	75–80	75–80
Annual rainfall (mm)	600–700	500–600	500–600	700–800
Total radiation (kcal/cm ²)	140–145	150–155	145–150	145–150

^a WGS84

Table 2 Biometric characteristics of the sampled maritime pine trees (mean and SD in parentheses) and site index

Stand	S1	S2	S3	S4
Site index ^a	DH (40)>17 m	DH (40)>14 m	DH (40)>18 m	DH (40)>21 m
Age	83 years	43–55 years	42–55 years	48–55 years
Number of sampled trees	20	5	5	5
Total height (m)	28.8 (2.8)	15.7 (3.4)	21.3 (1.0)	24.1 (1.0)
Crown height(m) ^b	8.7 (2.6)	7.7 (3.5)	9.1 (1.9)	10.0 (2.0)
Dead crown base (m) ^c	16.0 (2.1)	7.7 (1.2)	7.8 (1.3)	8.0 (1.6)
DBH (cm)	47.8 (7.3)	28.0 (2.3)	38.9 (9.2)	42.7 (5.3)
Volume over bark (m ³) ^d	2.7 (0.7)	0.5 (0.1)	1.3 (0.6)	1.6 (0.1)
Volume under bark (m ³)	2.3 (0.6)	0.4 (0.0)	0.9 (0.4)	1.2 (0.2)

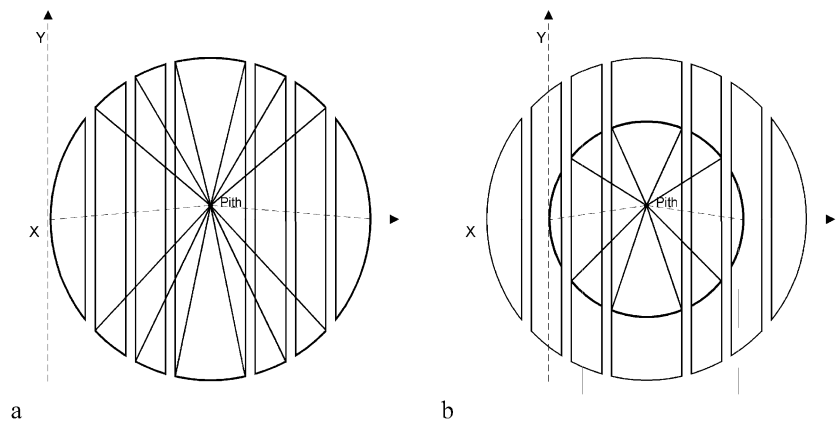
^a Dominant height (DH) at 40 years (Tomé et al. 1998)

^b Crown height = total height—live crown base height; crown base at the simultaneous occurrence of two green branches

^c Height from tree base to the first visible dry branch

^d Precise cubic method, Smalian formula

Fig. 1 Schematic representation of a log cross-section showing the position of the flitches, sawkerf and vectors from the pith to the outline points of stem (a) and heartwood (b)



conditions of each site and Table 2 gives the biometric data for the sampled trees.

The trees were harvested, and bucked into 5 and 2.5 m logs, where the north-south orientation was marked. Wood discs (5 cm thick) were taken for growth ring analysis at the bottom end of each log and at the top end of the top log.

Mathematical reconstruction of logs and stems

The 35 sampled trees were transformed into a set of virtual stems by mathematical reconstruction based on the so-called flitch method as described in Pinto et al. (2003). The trees were cross cut into 2.5 and 5 m logs (total of 133 logs) which were live sawn into 25-mm thick flitches. The flitches were scanned using the WoodCIM camera system providing RGB (colour component) information and the scanned images were computed using VTT's PuuPilot software. On the image of the flitch and with assistance from the operator, the system registered in data files, as x , y -coordinates, the geometrical outline of the sawn surface, the log pith line and the location, size, shape and quality factor of each knot. The data concerning the geometrical and quality features of the flitch, together with its thickness and with the support of the north-south reference line to create the 3rd coordinate, were processed with a dedicated software producing a mathematical reconstruction in x , y , z -coordinate system of a log or of a stem by addition of the different logs from one tree (Usenius 1999). Cross-sections of the log/stem were described with a set of 24 radial vectors between pith and the flitches and slabs' outline points along the log length at 50 mm intervals (Song 1987, 1998).

Virtual reconstruction of the heartwood

In the scanned images of all flitches, the heartwood was singled out from the sapwood by colour difference and its external outline was marked for further computing by the PuuPilot software. The individual flitch files pertaining to one log, with the data concerning the geometric features of the heartwood, were processed with the WoodCim® module software with the same algorithms and methodology described above for the log/stem geometry. Therefore a 3D representation of the heartwood along the log was obtained. The heartwood in the stem was subsequently reconstructed by joining the different logs from the same tree.

The heartwood data were further integrated with the reconstructed logs' data (shape and knot internal structure) based on the common pith xyz points, thereby producing a new 3D reconstruction including the geometrical description of the outer shape of the log, the internal knot architecture and the shape of heartwood. Figure 1 shows the construction and integration of the stem and heartwood shape in a transverse section.

Heartwood and sapwood contents

Based on the virtual stems' descriptive files, the amount of sapwood and heartwood was computed for each 50 mm of stem height by using the following variables: stem, heartwood and sapwood diameter, area and volume and respective proportions in the stem.

The stem and heartwood diameter at a certain height level are the double value of the average of all radial vectors that define the cross-section at that level and were used to calculate stem and heartwood cross-sectional areas. The volume for each stem height section was calculated as a conical trunk by the Simpson formula:

$$\text{volume} = \left(\frac{\text{height}}{3} \right) \times \left(\text{area1} + \text{area2} + \sqrt{\text{area1} \times \text{area2}} \right) \quad (1)$$

The sapwood area and volume were calculated as the difference between the corresponding values for stem and heartwood.

Data validation

The validation of the heartwood and sapwood reconstruction was made by a comparison with calculations based on growth ring measurements made directly on the wood discs taken from each log. The wood discs were sanded and the growth rings within heartwood and sapwood were counted and measured on two radii (S1, E-W) or on eight radii (S2-S4, N-S, E-W, SW-SE, NW-NE).

The virtual stem diameters had been previously compared with field measured diameters (Pinto et al. 2003). The difference between modelled and field diameter values was below 1% of the measured values except for the 20 m level where the modelled diameter was 4% higher than the measured one.

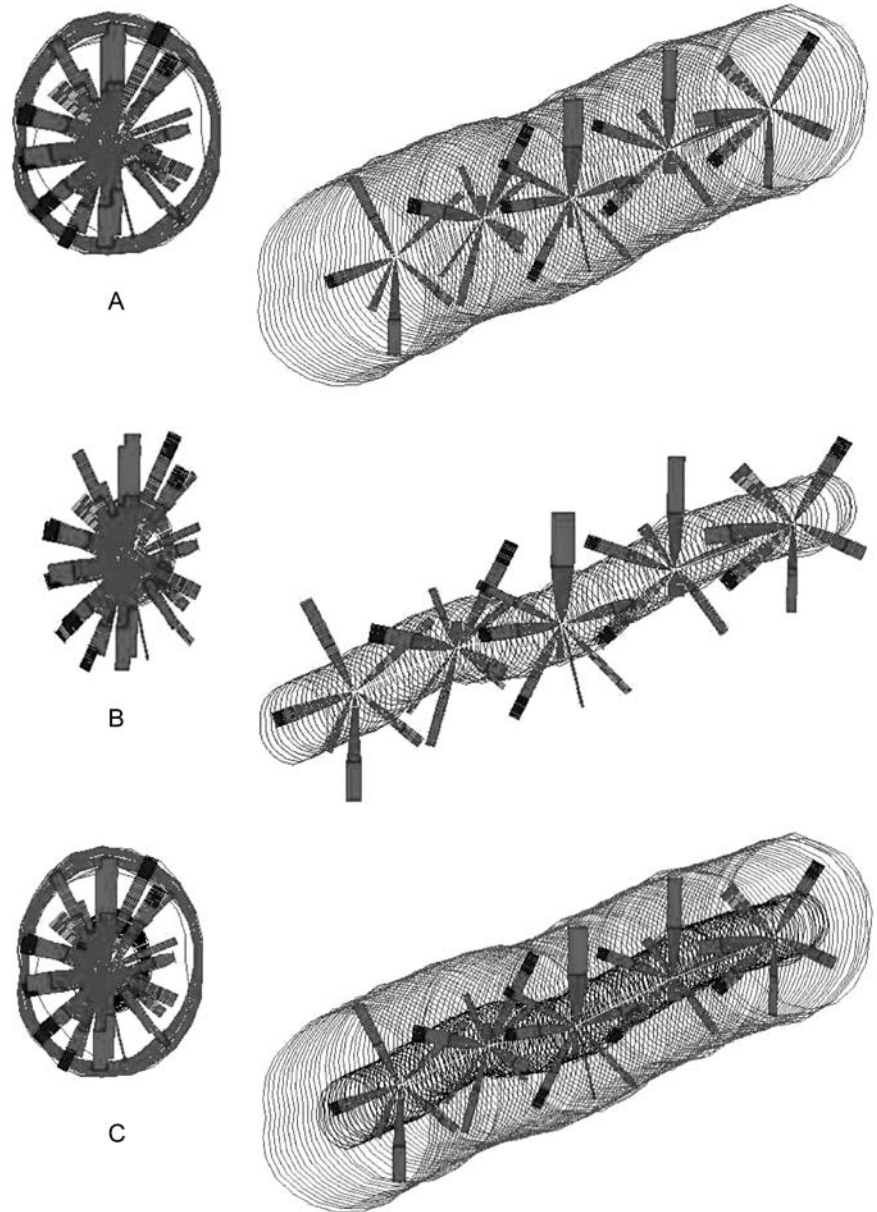
Results

3D reconstructed models

The results obtained for the reconstruction of logs and stems including the heartwood are exemplified in Fig. 2 for one log showing the stepwise procedure as a 3D view and as a 2D projection on the transverse plane. The associated files include information on stem and heartwood geometry as well as on the quality and dimensions of each knot in cross-sections for each 50 mm of stem height.

The heartwood was present in all the logs with the exception of the six top logs where the amount of

Fig. 2 Mathematical reconstruction of one maritime pine log showing in two and three dimensions, the geometry of the log and the internal knot architecture (A), the heartwood and the internal knot architecture (B) and the full model with the integration of both



heartwood was too low to be used in the reconstruction algorithm.

The accuracy of the reconstructed heartwood diameters was calculated by comparison with measurements taken on the wood discs. On average, the modelled diameters were 4% below the measured ones, ranging from -12.9% to +8.4% at the different height levels. The correlation between modelled and measured diameters was highly significant ($P < 0.001$, $R^2 = 0.88$) and shows very few outliers (Fig. 3).

Variation of heartwood with age

The number of growth rings included in the heartwood increased with cambial age for all the trees and sample

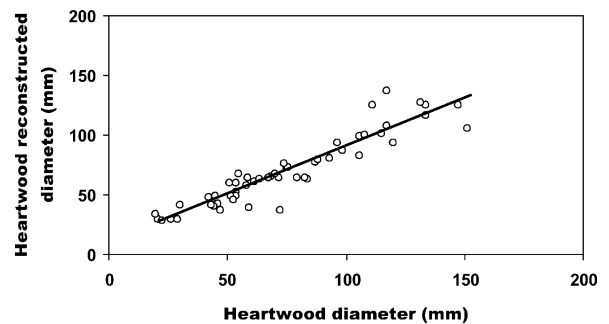


Fig. 3 Correlation of modelled heartwood diameters with diameters measured on the wood discs

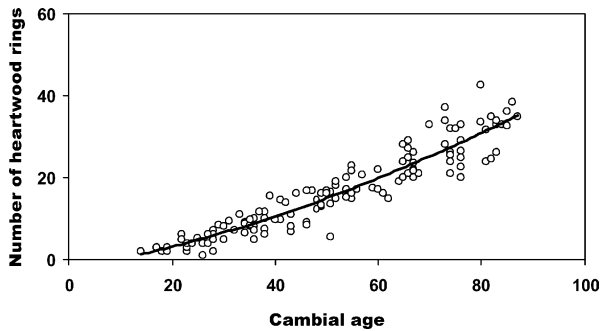


Fig. 4 Evolution of the number of heartwood rings with cambial age and fitted model ($H_{twr} = -2.400 + 0.231 \text{ age} + 0.002 \text{ age}^2$, H_{twr} number of heartwood rings, age cambial age at the same level)

Table 3 Average, minimum, maximum and standard deviation values for the heartwood annual formation rates for cambial ages over and above 55 years

	Average	Minimum	Maximum	SD
Number heartwood rings/year				
<55 years				
S1	0.50	0.34	0.72	0.11
S2	0.33	0.22	0.56	0.15
S3	0.51	0.32	0.80	0.18
S4	0.34	0.14	0.46	0.13
>55 years				
S1	0.70	0.21	1.75	0.46

sites (Fig. 4). A total of 138 samples were measured with cambial age between 14 and 87 years. Regression analysis indicated that a second degree polynomial best predicted the number of heartwood rings as a function of cambial age ($P < 0.001$, $R^2 = 0.89$) but a linear fitting also showed a good and high significance adjustment ($P < 0.001$, $R^2 = 0.88$). By extrapolation the heartwood initiation age was found to be 13 years with the second degree fitting, and 18 years with the linear fitting. In the samples studied, the first phases of heartwood formation (1–3 heartwood rings) were found in discs with cambial ages ranging from 13 to 28 years.

A regression analysis for different cambial age groups (below and above 55 years) indicated that heartwood forms, in average, at a higher rate for older ages (0.7 rings/year) than for younger ages (0.5 rings/year). However this rate was variable for individual trees within the studied sites (Table 3).

The variation of heartwood formation with age may also be followed by analysis of within tree variation, along the stem height, of the number of heartwood rings (Fig. 5). The number of heartwood rings decreased with tree height following the decrease in the total number of growth rings. However the proportion of heartwood rings slightly increased or remained constant in the lower part of the stem and decreased afterwards in the upper part of the stem, following the differences in cambial ages along stem height. The same difference was noticed between S1

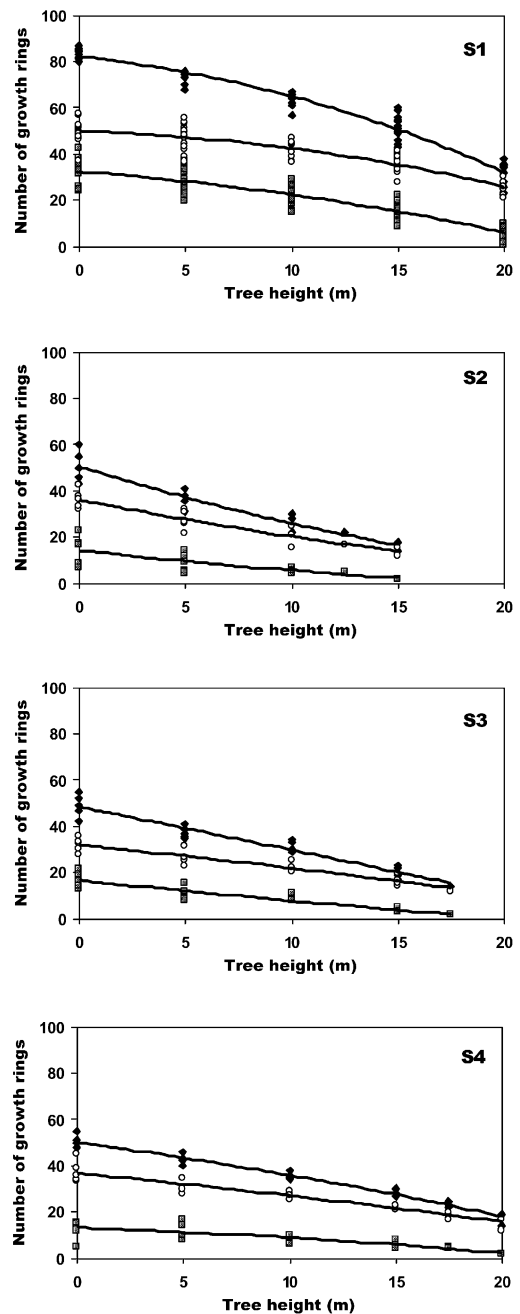


Fig. 5 Variation of total (diamonds), heartwood (squares) and sapwood (circles) growth rings along tree height for sampled sites S1–S4

and S2–S4 stands as a result of the tree age difference. In the older trees of S1, the heartwood contained on average 39%, 37%, 30% and 18% of the total number of growth rings respectively at the base, 5 m, 15 m and 20 m height levels, while for the younger S2–S4 trees this proportion was 34%, 28% and 18% respectively at the base, 5 m and 15 m in height.

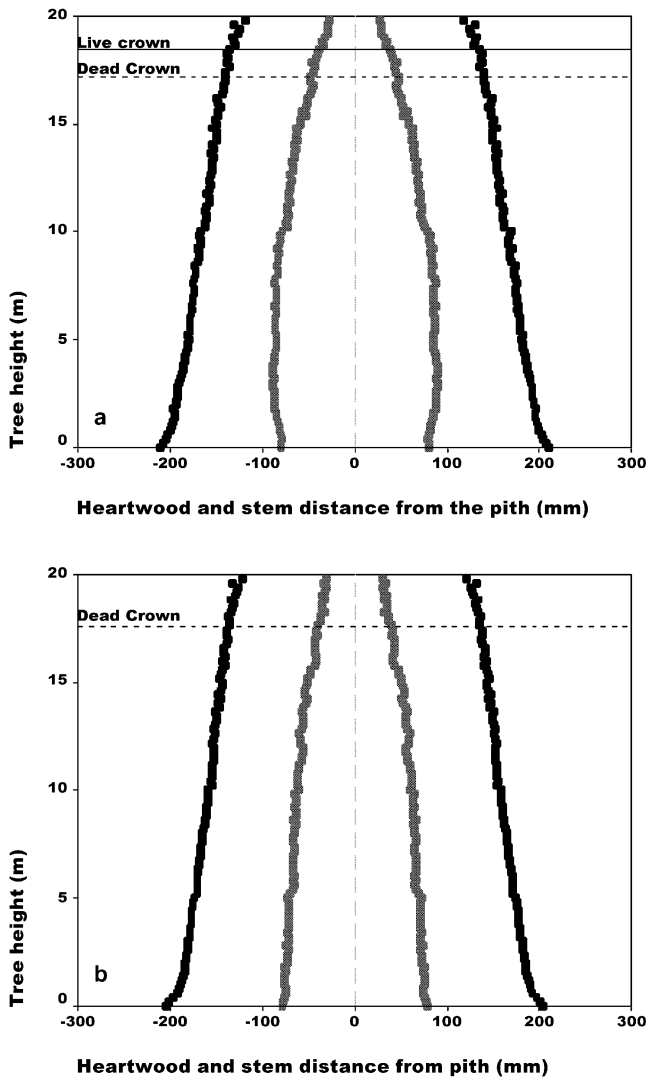


Fig. 6 Stem and heartwood profiles of two trees showing the two patterns of heartwood axial variation: (a) heartwood with a maximum diameter at a specific height; and (b) decreasing heartwood diameter along the stem

Heartwood and sapwood contents within the stems

Variation of heartwood along the stem

Figure 6 shows some examples for stem and heartwood vertical profiles. In the majority of the sampled trees (63% of the total) the heartwood radius increased from the stem base to a maximum and decreased afterwards until the top of the tree following the stem shape (Fig. 6a), but in some trees this maximum was not evident and heartwood tapered from the base until the top of the tree following the stem shape (Fig. 6b). The maximum heartwood radius was found at an average tree height of 3.8 m, with values ranging from 1.4 m to 6.8 m in the individual trees. For almost all trees the heartwood decreased at a faster rate after a certain height level located between the dead crown and live crown bases.

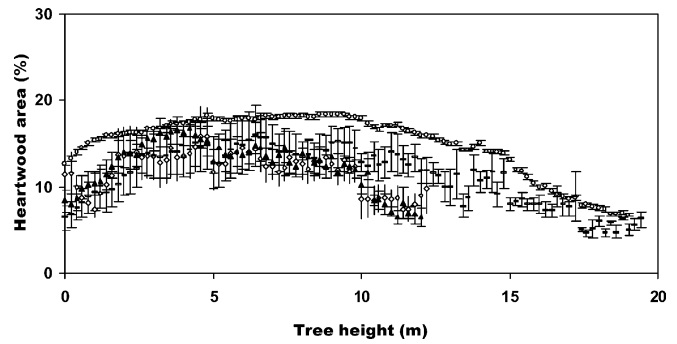


Fig. 7 Variation along stem height of the proportion of heartwood area in the stem cross section, for trees from S1 (circles), S2 (diamonds), S3 (triangle), S4 (oblong)

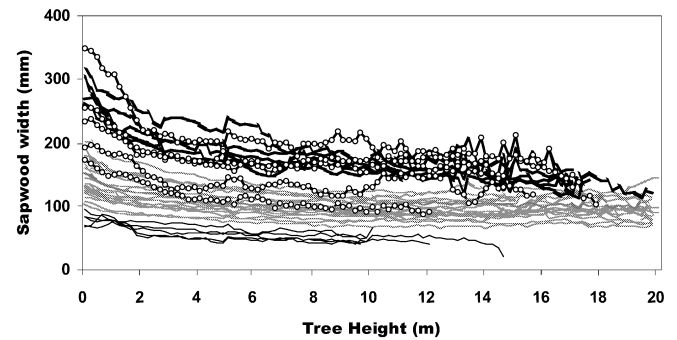


Fig. 8 Variation of sapwood width along stem height for sites S1 (grey line), S2 (thin line), S3 (dotted line) and S4 (thick line)

These variations are more visible when observing the development along stem height of the heartwood area proportion in relation to the stem cross-section (Fig. 7). The proportion of heartwood area tends to increase from the stem base to a maximum between 4 and 9 m high and then decreases to the top at the base of the dead crown. The maximum proportion of heartwood was found in S1 at 8.8 m representing 42% of the diameter and 18% of the cross-sectional area, in S3 at 4.2 m with 41% and 17%, respectively, and in S4 at 6.8 m with 39% and 16%, while for trees in S2 the proportion of the heartwood remained rather constant with stem height at approximately 17% of the tree diameter and 13% of the cross-sectional area. The increase in the heartwood proportion is higher in the first 2–3 m of the stem.

Variation of sapwood along the stem

Sapwood width was higher at the stem bases and decreased during the first 2–3 m of tree height, remaining almost constant further on along the stem height for all trees and sites (Fig. 8). The sapwood width values were similar among trees in the same site except for S3, where between-tree variability was higher. The between-tree variability in the same site was higher at the stem base,

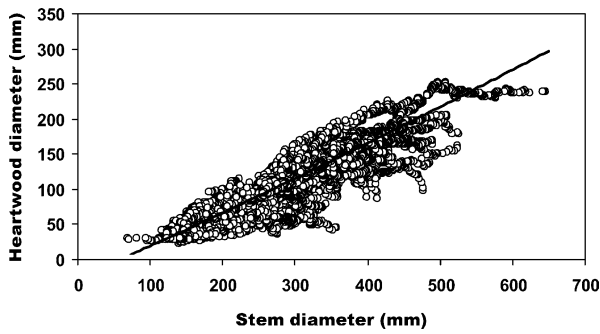


Fig. 9 Evolution of heartwood diameter with stem diameter and fitted model ($HtwD=7E^{-0.5} StemD^2+0.451 StemD -31.055$, $P<0.01$, $HtwD$ heartwood diameter, $StemD$ stem diameter)

e.g. coefficients of variation of the mean at this level ranged from 8–18% for S1, S2 and S4, to 28% in S3.

Relation of heartwood and sapwood with tree growth

As suggested by the analysis of the vertical profiles (Fig. 6), the heartwood diameter correlated strongly with the stem diameter. When considering data for all height levels of all the trees ($n=11,997$) the heartwood diameter and area showed a correlation with stem diameter of 0.89 and 0.87 respectively ($P<0.01$). When evaluating this relation for one specific height level ($n=35$), the correlations were equally high and significant (Table 4).

Figure 9 plots the stem and heartwood diameter values for all height levels of all sampled trees. For predicting heartwood diameters based on stem diameters, a second degree polynomial proved to be the best fit and accounted for 80% of the variation. According to the model, heartwood will be present for stem diameters above 6.8 cm and will increase in diameter by approximately 0.5 cm per centimetre of stem diameter increase. A linear regression also gives a good adjustment ($R^2=80\%$).

Further correlations with stem diameter are shown in Table 4. The sapwood width and cross-sectional area showed very high and positive values. The heartwood diameter proportion in percent of tree diameter correlated positively with the stem diameter but the coefficient of correlation was low and only significant at 20% of the total tree height and for all height levels.

The sapwood cross-sectional area at the live and dead crown bases had a positive and significant correlation

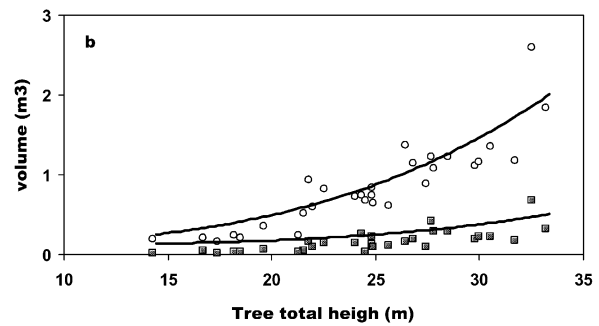
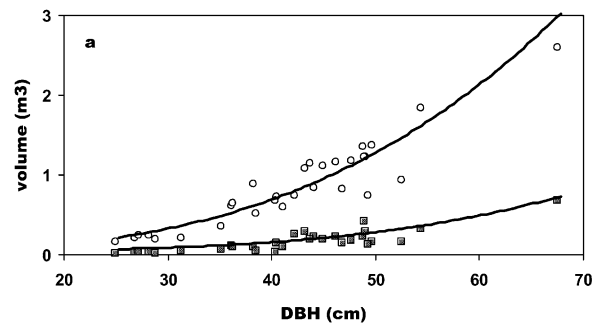


Fig. 10 Heartwood (squares) and sapwood (circles) volume as a function of DBH (a) and tree height (b), for all sampled trees

with DBH and tree total height. For S1 trees it was possible to analyse this relation with crown variables. It was found that the sapwood cross-sectional area at the crown base had a stronger and more significant correlation with the crown basal area (0.83**) than with the crown height (0.30*).

Heartwood and sapwood volumes

Heartwood represented about 17% of the stem volume in 50% of the total tree height, for S1, while for the younger stands (S2–S4) this proportion was 12–13%. For the older trees of S1, the proportion of heartwood in stem volume, on average, was 12% at the stem base, increasing to about 18% between 4–9 m in height and decreasing to 7% at 20 m high. The younger trees from S2–S3 stands showed lower proportions of heartwood volume with about 9%, 14% and 7% at the stem base, between 3 and 5 m in height, and 15 m high, respectively.

Table 4 Correlation between heartwood and sapwood dimensions and heartwood content with stem diameter for S1–S4 trees calculated using data for all height levels (for each 50 mm of stem height, $n=11,997$) and two fixed height levels (20% and 50% of total height, $n=35$)

Stem diameter	All height levels	50% of total height	20% of total height
Heartwood diameter	0.90**	0.87**	0.90**
Heartwood area	0.87**	0.83**	0.88**
Heartwood in % diameter	0.47**	0.31	0.39*
Sapwood width	0.90**	0.91**	0.89**
Sapwood area	0.98**	0.98**	0.98**

* Pearson correlation is significant at the 0.05 level (2-tailed)

** Pearson correlation is significant at the 0.01 level (2-tailed)

Table 5 Correlation between heartwood and sapwood volumes and tree biometric variables for S1–S4 trees. Stem, heartwood and sapwood total volume is the volume in 50% of total tree height

	Heartwood volume	Sapwood volume	Heartwood volume %
Stem volume	0.93**	1.00**	0.67**
DBH	0.83**	0.92**	0.39*
Tree total height	0.73**	0.87**	0.31
Height live crown	0.72**	0.76**	0.47**
Height dead crown	0.61**	0.71**	0.29
Crown height	0.18	0.42**	-0.21

Pearson correlation, $n=30$, **correlation is significant at the 0.01 level (2-tailed), *correlation is significant at the 0.05 level (2-tailed)

Table 5 shows the correlations between heartwood and sapwood volume and tree biometrics. The volumes were calculated up to 50% of the total tree height in order to minimise differences between trees. The sapwood volume of S1 trees showed a positive relation with crown area and height ($R^2=0.71$ and 0.75 respectively). The sapwood and heartwood volumes were found to be strongly correlated with total tree height (Ht) and DBH (Fig. 10).

Discussion

The heartwood content increases with tree age and various authors found evidence that, after a certain initiation age, heartwood is formed at a constant annual ring rate (Hazenberg and Yang 1991; Wilkes 1991; Sellin 1994; Bjorklund 1999; Gjerdrum 2002).

For maritime pine it was possible to predict the number of growth rings included in the heartwood with cambial age through a second degree polynomial model (Fig. 4). The heartwood formation rate was slower in younger ages with 0.5 rings year⁻¹ for ages under 55 years and 0.7 rings year⁻¹ between 55 and 83 years. For trees with similar ages (S2–S4), the variability in the number of annual rings within heartwood at a certain height level (Fig. 5) was quite low which supports the theory that heartwood progresses at a constant rate along the stem diameter.

These results parallel those of Björklund (1999) for *Pinus sylvestris* L. This author also found a second degree polynomial as the best fitting for this relation and similar heartwood development rates of 0.5 , 0.7 and 0.9 rings year⁻¹ for ages below 45, and around 90 and 115 years, respectively. For the same species, Gjerdrum (2002) predicted the number of heartwood growth rings from the square root of cambial age, finding rates of 0.6 rings year⁻¹ for a cambial age of 60 years and 0.8 rings year⁻¹ at 220 years.

In *Picea mariana*, Hazenberg and Yang (1991) also found a quadratic relation between heartwood rings and cambial age and registered lower heartwood development rates in younger than in older trees, though higher than those found for maritime and Scots pine (0.79 rings year⁻¹ at 50 years and 0.98 at 90 years).

In the present study the age of heartwood initiation was estimated to be 13 years through extrapolation of the model, while in the measured samples the first phases of heartwood formation (1–3 heartwood rings) were ob-

served in discs with cambial ages between 13 and 38 years. Esteves (2000) estimated heartwood initiation age for maritime pine to be around 20 years based on observation of stem discs at various height levels. For other pine species, heartwood initiation ages between 9 and 15 years were found by extrapolation for Scots pine (Bjorklund 1999; Gjerdrum 2002) and by direct observations, at 11 years for the same species (Morling and Valinger 1999), and 30 years for *P. canariensis* (Climent et al. 2003).

The age of heartwood formation is usually lower when estimated by fitted models than by observation of wood discs. This calls attention to the need for more data on the very early phases of heartwood formation in order to strengthen the models due to a probably higher between tree variability for the initiation of this process. Heartwood formation is under a strong genetic control though its initiation age can be influenced by environment and forest practices (Hillis 1987). This may explain the variability found for this value for the same species as given by different authors. In accordance with the previous discussion, the number of growth rings included in the heartwood decreased with stem height with a higher slope in the upper parts, leading to a decrease in the proportion of rings included in the heartwood at these stem height levels (Fig. 5).

The within tree development of heartwood and sapwood could be followed using the virtual stem reconstruction. It was possible to introduce heartwood data in the WoodCim[®] reconstruction software and to obtain a clear visualisation of its geometry together with stem geometry and knots size, position and quality (Fig. 2). These are important quality features of maritime pine stems and the information associated with the 3D models allows their study and quantification. The reconstruction of heartwood shape was a new feature added to the reconstruction module that has been already applied to the maritime pine sampled trees (Pinto et al. 2003).

For a few trees the heartwood diameter at the highest tree height levels was less or slightly more than 25 mm and accurate reconstruction was not possible since the measurements were based on a 25 mm flitch thickness. Future studies with stem parts with low heartwood content would require the use of thinner flitches for data acquisition.

The accuracy of the model regarding heartwood diameter was good and in the range previously found for stem reconstruction (Fig. 3). Differences between

heartwood diameters measured on wood discs with the reconstructed ones may arise from the different number of diameter measurements taken for the average (4 diameters in the wood discs and 12 given by the model for each cross-section), as well as from reconstruction errors at the junction of logs where the discs were taken out and the missing values had to be extrapolated.

However, the main source of differences between modelled and measured heartwood diameters was the natural irregularity of the stem shape, and they increased with pith curviness. This also occurred for stem reconstruction, where the difference between modelled and field measured stem diameters for S1 and S2–S4 logs, respectively with 14.5 mm and 27 mm average pith curviness (Pinto et al. 2002), was on average below 1% for S1 (Pinto et al. 2003) and 4% for S2 to S4 sites.

Since in maritime pine the heartwood cross-section tends to be irregular at the tree base and more regular with increasing stem height, in connection with reaction wood formation (Stokes and Berthier 2000), the description given by the model with a higher number of radial and axial measurements will better account for this irregularity and the along the stem variation of heartwood and sapwood in cross-section. Differences in stem shape between the sampled groups are related with their silviculture. In the state-owned Leiria forest (S1), with a management oriented to produce wood raw material for high added value timber products, the stems were straighter and less tapered than in the private-owned pine stands (S2–S4), without cultural operations or cleaning of undergrowth vegetation.

Overall, the within and between tree variation of heartwood and sapwood found here for the maritime pine stems follows the results reported in the literature for pine species.

Maritime pine sapwood width was much higher at the stem base than further up in the stem where it stabilized at an almost constant value after 2–3 m (Fig. 8). These results are in accordance with findings for this species (Stokes and Berthier 2000) as well as for *P. sylvestris* (Björklund 1999) where sapwood width also showed constant values after 3 m height. Stokes and Berthier (2000), following Gartner (1991) and Zimmerman (1983), commented that this higher amount of sapwood at the tree bases might be connected with a decrease in specific conductivity in this region that is compensated by a higher sapwood area.

The variability of heartwood dimensions was quite high, both between trees and between stands, in contrast to sapwood width which showed lower variation for trees belonging to the same stand. The proportion of heartwood area in the stem cross-section reflected the heartwood profile along stem height (Fig. 7) but with lower variability between tree and stand. After the crown base level there was a clear increase in the sapwood proportion.

The relation between sapwood cross-sectional area at the crown base and foliage mass was not investigated in this study. However, the sapwood area at this level and

the total sapwood volume within 50% of the tree height showed significant relations with crown dimensions (area and height) and is thereby in accordance with the pipe-model theory (Shinozaki et al. 1964).

The heartwood diameter either decreased with stem height or presented a maximum value at a specific height decreasing afterwards until the top of the tree (Fig. 6). Climent et al. (2003) also reported the occurrence of these two patterns for Canary Island pine and classified them as uniform in the first case and irregular in the second. This latter was the usual pattern for the majority of the sampled maritime pine trees and the maximum heartwood diameters were found between 1.4 m and 6.8 m. Similar profiles have been found for maritime pine in France, Spain and Portugal (Stokes and Berthier 2000; Esteves 2000; Berthier et al. 2001; Ezquerro and Gil 2001; Ferreira 2002), and for other pine species such as Scots pine (Björklund 1999; Mörling and Valinger 1999), Canary Island pine (Climent et al. 2003) and radiata pine (Wilkes 1991).

Since heartwood starts to form at a given height level and proceeds upwards and downwards along the stem (Hillis 1987) larger diameters and a higher heartwood proportion in this region are expected. In S1 trees, the maximum proportion of heartwood in the stem cross-section was found at 8.8 m, which, according with the production tables for that site, corresponded to total tree height at about 13 years of age. This was in fact the age that was estimated here for heartwood initiation.

Recently, Climent et al. (2003) have hypothesized that the peak in the heartwood vertical profile may be due to an earlier (or faster) heartwood formation in this region caused by tree sway related to the crown depth. In fact eccentric heartwood formation is related to stem eccentricity and reaction wood production (Hillis 1987; Stokes and Berthier 2000; Berthier et al. 2001), even though heartwood does not increase the bending stiffness of the trunk (Berthier et al. 2001). In *P. canariensis*, Climent et al. (2003) observed that trees with irregular heartwood had crowns in the upper half of the stem which created larger bending momentum.

However, this was not the case for the maritime pine trees studied here where the pattern of heartwood vertical variation was not related to crown dimensions. For instance in stand S2, where all the trees had an uniform heartwood profile, crown base was situated, on average, at 64% of tree height while in sites S1, S3 and S4, where most trees showed irregular profiles, these values were, 57, 59 and 70% respectively. Moreover, no relations between the crown projection area and height and heartwood profiles were found for S1 trees. The heartwood irregular profiles are therefore likely to be due to other factors, i.e. as a consequence of the increased sapwood volumes and butt swell at the stem bases.

Since heartwood develops in the tree at a constant annual rate, it is expectable that its amount will be significantly correlated with the tree biometry and variables that influence its diameter growth. This was found in this study (Table 4). Stem diameter was the best

predictor of heartwood diameter (Fig. 9). The adjustment was done through a second degree polynomial indicating that heartwood diameter will increase by approximately 0.5 cm for each centimetre of stem diameter.

Tree total height and diameter at breast height showed the highest correlation with heartwood and sapwood total volume within the tree (Table 5). Climent et al. (2003) also found total tree height and heartwood diameter at breast height as the best predictors for heartwood volume in *Pinus canariensis*. However, using considerable data from a stem bank, Björklund (1999) concluded that it is not possible to predict, using inventory data, which are the stands with higher heartwood volume production due to the high variability between trees and stands. Therefore it is necessary to increase sampling before attempting to use these two variables to predict heartwood volumes, and the correlations shown here are only indicative.

The hypothesis of predicting heartwood diameters based on stem diameters and of heartwood volumes based on tree height and DBH can be very useful for tree utilization as a raw material for the wood-based industry. When the target is to maximize heartwood content in the products, the trees can be selected by DBH and height at harvest and stem bucking can be optimized taking into account the within-stem variation of heartwood.

In conclusion, the data obtained in the present study increased our knowledge of the heartwood and sapwood development within maritime pine trees. The inclusion of heartwood in the algorithms for the stem virtual 3D-reconstruction allowed an accurate description of its volumes within a stem and, therefore, a detailed characterisation of the within-tree heartwood and sapwood development. This has a high potential of application in further studies once a sufficiently large number of trees is studied in order to account for the observed between-tree and between-stand variability. The evidence found here for maritime pine accords to the theory that heartwood initiation is an age related process, and that its development within the tree is age and growth related.

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