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Original article

Heartwood and sapwood variation in *Eucalyptus globulus* Labill. trees at the end of rotation for pulpwood production

Maria C. MORAIS[a,b], Helena PEREIRA[a*]

[a] Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade Técnica de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal
[b] Departamento de Botânica, Universidade de Coimbra, Calçada Martim de Freitas, 3000-355 Coimbra, Portugal

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Abstract – The amount of heartwood and sapwood in *Eucalyptus globulus* Labill. wood was determined in commercial pulpwood plantations at harvest age (12 to 15 years) in four ites in central portugal. twelve trees were sampled in each site at nine stem height levels. Heartwood was present in all the trees up to 82%–87% of the total tree height and amounted to 38%–41% of the total tree volume. The heartwood proportion in the stem cross-section decreased from the base upwards, representing 53.3% and 26.1% of the total area respectively at the base and 55% height level. The sapwood width remained relatively constant along the stem at a mean 38 mm up to the 55% height level. The trees within the site, the height level and their interaction were highly significant sources of variation for heartwood proportion and sapwood width. The heartwood diameter and sapwood width were positively correlated with radial tree growth.

***Eucalyptus globulus* / sapwood / heartwood / tree growth / pulping**

Résumé – Variation du bois de cœur et de l'aubier de *Eucalyptus globulus* Labill. pour la production papetière. La quantité de bois de cœur et d'aubier dans les arbres d'*Eucalyptus globulus* Labill. a été déterminée dans des plantations commerciales pour l'industrie papetière à l'âge de rotation 12 à 15 ans dans quatre sites au centre du Portugal. Douze arbres ont été prélevés dans chaque site à neuf niveaux. Chaque site est représenté par douze arbres et chaque arbre par neuf disques à différentes hauteurs. Le bois de cœur était présent dans tous les arbres jusqu'à 82 %–87 % de la hauteur et représentait 38 %–41 % du volume. La proportion de bois de cœur dans la section transversale de la tige diminuait de la base vers le sommet, correspondant à 53,3 % et 26,1 % de la surface totale, respectivement à la base et au niveau de 55 % d'hauteur. La largeur de l'aubier est demeurée relativement constante au long de l'arbre à une moyenne de 38 mm jusqu'au niveau de 55 %. Les arbres dans le site, le niveau d'hauteur et leur interaction ont été des sources de variation fortement significatives pour la proportion de bois de cœur et la largeur de l'aubier. Le diamètre du bois de cœur et la largeur de l'aubier ont été corrélés positivement avec la croissance radiale de l'arbre. La proportion de bois de cœur et la largeur d'aubier sont expliquées par l'effet arbre dans le site et par la hauteur dans l'arbre. Le diamètre du bois de cœur et la largeur d'aubier sont corrélés positivement avec la croissance radiale.

***Eucalyptus globulus* / aubier / bois de cœur / croissance de l'arbre / pâte à papier**

1. INTRODUCTION

The wood of *Eucalyptus globulus* Labill. is an important source of papermaking fibres in the pulp industry, combining first quality pulp and paper properties with tree fast growth and short rotations [7]. In addition to other wood characteristics, e.g. anatomical and chemical properties, the suitability of eucalypts for papermaking is influenced by the extent of heartwood and of sapwood within the pulpwood logs. Heartwood has a negative influence on the pulping quality increasing chemical consumption in pulping and bleaching, decreasing pulp yield and pulp brightness, and increasing process costs [20]. For the pulp and paper industries, logs with wider sapwood are preferred.

In the living tree, the sapwood, in contrast with heartwood, is physiologically active, conducting water and nutrients from roots to leaves [2, 13] and storing food materials [2]. The transformation of sapwood into heartwood is characterized by the death of parenchyma cells [13], development of tyloses in the vessels of many species [1] and the biosynthesis of non-structural compounds, leading to an important accumulation of extractives and to the differences in physical and chemical properties between sapwood and heartwood [23]. Heartwood and sapwood in a tree vary with a large number of factors, including species, age, climate, rate of growth, foliage area, site quality and tree vitality, and have been the subject of several reviews [1, 11–13, 16, 19, 25, 29].

The initiation and rate of transformation of sapwood into heartwood are explained by several theories, namely that it is the amount of sapwood, e.g. area or radial width that regulates the amount of heartwood [1, 13]. However data are scarce and are sometimes contradictory, regarding the effect on sapwood width of tree age [10, 11, 23, 30] or of tree growth [3, 8, 27].

In eucalypts, studies on heartwood have been made for several species, e.g. *E. camaldulensis* [12], *E. tereticornis* [22], *E. marginata*, *E. maculata* [2], *E. delegatensis*, *E. dalrympleana* [13], *E. grandis* [28], *E. globulus* [8, 18], *E. grandis* × *E. urophylla* [7], and the proportion of heartwood was shown to vary substantially between species [2, 5]. In *E. globulus*

* Corresponding author: hpereira@isa.utl.pt

Table I. Site and stand descriptions.

	Crato	Sertã	V. F. Xira	Azambuja
Latitude	39° 02' N	38° 45' N	39° 04' N	39° 04' N
Longitude	07° 38' W	08° 07' W	09° 00' W	08° 52' W
Altitude (m)	200–300	200–400	0–100	0–100
Mean annual rainfall (mm)	700–800	700–1000	500–600	500–800
Mean temperature (°C)	12.5–15	15–16	15–16	15–17
Soil type	Eutric litosoils	Eutric litosoils	Calcic cambisoils	Cambisoils
Year of planting	1985	1986	1988	1988
Age at felling (years)	15	14	12	12
Spacing (m × m)	3 × 3	4 × 2	4 × 2	4 × 2
Annual yield (m^3/ha/year)	9	16	10	11
Average total volume (m^3/ha)	135	224	147	130

trees at harvest age for pulping, the volume of heartwood is significant, corresponding to approximately one third of the stem volume, and important between-tree and between-site variation was reported [8]. However, there is still little information on the variability of sapwood and heartwood content in commercial plantations of *E. globulus* trees for pulp production that could lead to silvicultural or improvement guidelines.

In this paper we report data on the within and between-tree variability of sapwood and heartwood in four commercial plantations of *E. globulus* at the time of harvest for pulp production, and analyse the influence of radial tree growth in the perspective of a plantation management oriented towards the pulp and paper industry.

2. MATERIAL AND METHODS

The study was made on the first rotation of commercial *E. globulus* Labill. plantations located in Central Portugal: Crato, Sertã, V. F. Xira and Azambuja. The plantations were established using a commercial seed source by the pulp company Celbi (StoraEnso) with the silvicultural techniques used in Portuguese eucalypt forestry. Site and stand descriptions are given in Table I.

Twelve trees, not located near the stand border and with no evidence of damage or disease, were randomly harvested in each site and were characterized by measuring diameter over bark at breast height (1.3 m) and stem height (Tab. II).

Within tree, 5 cm thick discs were taken at different stem height levels: at the base, at 5% of total height and subsequently at intervals of 10% up to 65% and at 90% of total tree height, that corresponded to a diameter of approximately 7 cm and the limit of the commercial stem.

These discs were analysed in the laboratory. The heartwood delimitation was made by visual observation of the wood disc cross-section; in *E. globulus*, the heartwood shows a distinctive brown colour compared to the lighter coloured sapwood. The total disc cross-section and the heartwood area were measured using an image analysis system as previously described [8]. The sapwood area was obtained by difference and calculation of mean heartwood diameter and sapwood radial width was made subsequently.

The height attained by the heartwood within the tree was estimated from the linear adjustment of heartwood diameter as a function of tree height made individually for each tree (r values were on average 0.981) for a zero heartwood diameter.

Table II. Diameter at 1.3 m height (D.b.h.) and total height of the trees sampled at the four sites. Average of twelve trees per site; in brackets the standard deviation.

Site	D.b.h. (cm)	Tree height (m)
Crato	13.23 (1.51)	20.42 (2.64)
Sertã	13.83 (2.18)	25.25 (2.04)
V. F. Xira	13.88 (3.18)	19.35 (2.30)
Azambuja	14.33 (2.96)	20.18 (2.86)

The tree and heartwood volumes were estimated by stem sections, corresponding to the different height levels, using formulas for a cylinder for section 0%–5%, truncated cone for all intermediate sections (5%–15% to 65%–90%) and a cone for the tree top (90%–top).

The data were statistically analysed with STATISTICA 6.0 software. A simple regression model (response variable = $\beta 0 + \beta 1$ independent variable + ε) was applied to study the correlations between heartwood height and tree height, heartwood volume and tree volume, heartwood diameter, proportion of heartwood and sapwood width as a function of the tree diameter. Analysis of variance (ANOVA) was used, in each site, on the variables heartwood proportion and sapwood width. The sources of variation were trees (random effect, $n = 12$), height level (fixed effect, $n = 9$) and the interaction of the height level and trees.

3. RESULTS

3.1. HEIGHT OF HEARTWOOD

The mean values of heartwood height, heartwood-free stem length and proportion of heartwood within the tree can be observed in Table III. Heartwood was present in all the trees and attained levels corresponding to 82.1% to 87.2% of total tree height. Heartwood was not found at the 90% height level and 10 trees also showed no heartwood at the 65% height level.

Between sites there were no significant differences of heartwood proportion and heartwood-free stem length; the heartwood height was larger in Sertã, the site with the tallest trees (Tab. I).

As shown in Figure 1, the height of heartwood presents a highly significant correlation with tree height ($H_{heartwood} = -2.298 + 0.957\, H_{total}$, $r = 0.84$, $P < 0.000$, $H_{heartwood}$ and H_{total} in m).

Table III. Within tree height attained by the heartwood, length of the heartwood-free stem, proportion of heartwood in tree height (%), stem wood volume, heartwood volume and proportion of heartwood in tree volume. Average of twelve trees per site, in brackets the standard deviation.

	Crato	Sertã	V. F. Xira	Azambuja
Heartwood height (m)	16.81 (3.14)	22.04 (3.26)	16.15 (2.86)	17.35 (3.29)
Heartwood-free stem length(m)	3.60 (1.81)	3.21 (2.32)	2.79 (1.84)	2.27 (1.40)
Heartwood height (% total)	82.1 (8.6)	87.2 (9.6)	83.9 (13.4)	85.6 (7.9)
Stem volume (m^3)	0.116 (0.035)	0.176 (0.054)	0.135 (0.082)	0.138 (0.074)
Heartwood volume (m^3)	0.045 (0.019)	0.071 (0.027)	0.053 (0.037)	0.056 (0.031)
Heartwood volume (% total)	38.1 (6.5)	39.5 (5.8)	38.4 (4.6)	40.5 (4.9)

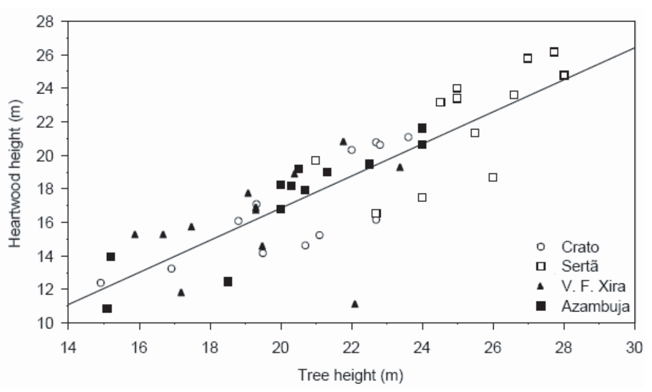

Figure 1. Relationship between heartwood height and tree height for the *E. globulus* trees in the four sites.

3.2. Heartwood and sapwood content

The heartwood and sapwood area within the stem cross-sectional area (Figs. 2 and 3, respectively) decreased with height in all sites. At the base and 5% height level, the heartwood area was almost higher than sapwood area and decreased afterwards until the top. At the highest level, the heartwood was absent.

The proportion of heartwood in the stem cross-section also decreased within the tree from base to the top (Fig. 4) with statistically significant differences for the mean values between the sites. At the base the heartwood proportion ranged 51.6%–55.0% of the total sectional area and decreased with a constant rate to the 55% height level where it ranged 24.5%–27.5%; from that point upwards the decrease was higher and at 65% of height heartwood represented 10.6%–14.7% of the cross section.

The analysis of variance for the proportion of heartwood (Tab. IV) was made for each site and showed that there was a very highly significant influence of trees, height level and the interaction between both factors. The decomposition of the variance by sources of variation showed that the effect of height level explained between 85% and 88% of the total variation while between-tree variation accounted for 5% to 9% of the total variation.

The radial width of sapwood (Fig. 5) remained relatively constant within the trees from the base to the 55% height level, corresponding to a mean value of 38.0 mm. Sapwood increased at the 65% height level to 49.2 mm and decreased from this level towards the top.

The analysis of variance of sapwood width (Tab. IV) showed that the effect of all sources of variation (trees, height level and the interaction height level × trees) were very highly significant ($P < 0.001$) in all sites. For the total variation trees accounted for 26% to 59%, height level for 16% to 31% and the interaction between trees and height level for 24% to 42%.

3.3. Heartwood volume

The average stem volume ranged between 0.116 m^3 in Crato and 0.176 m^3 in Sertã (Tab. III) corresponding to average tree growth rates of 0.008 m^3y^{-1} and 0.013 m^3y^{-1}, respectively. The proportion of heartwood was on average 39.1%, and showed no between-site variation.

The correlation between heartwood volume and tree volume was highly significant and a linear relationship was found (Fig. 6). If heartwood volume is regressed on tree volume, 94% of the variation in heartwood volume is explained by tree volume ($V_{heartwood} = -0.006 + 0.442\ V_{total}$, $r = 0.97$, $P < 0.000$, with $V_{heartwood}$ and V_{total} in m^3).

3.4. Influence of tree growth on heartwood and sapwood

The relationships between heartwood diameter and tree diameter in the four sites were positive and highly significant for all height levels.

Considering only one height level (15%), Table V shows the variation of heartwood diameter with stem diameter for all sites. A high and significant correlation between these two variables was obtained in each of the four sites. When all the trees were considered (Fig. 7) a high correlation between heartwood diameter and tree diameter was also found corresponding to the following model: $D_{heartwood} = -1.411 + 0.809\ D_{total}$ ($r = 0.94$, $P < 0.000$, with $D_{heartwood}$ and D_{total} in cm). The proportion of heartwood at this level showed a very poor correlation with tree diameter but significant ($r = 0.34$, $P < 0.018$).

The relationship between sapwood width and tree diameter at this 15% height level is shown in Table V for each site. No significant relationship was found for Crato and Sertã while

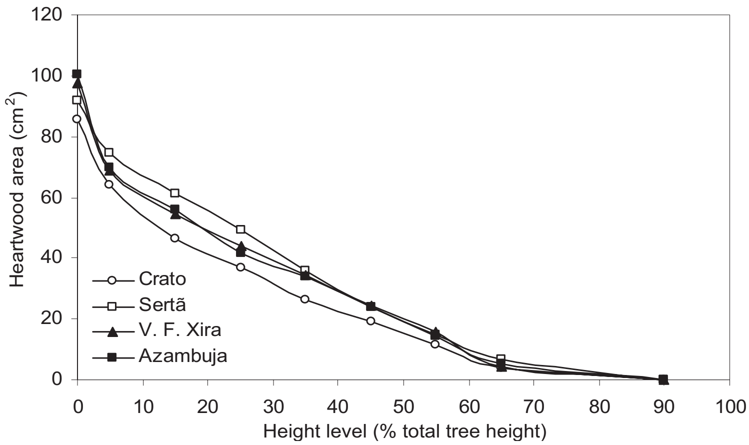

Figure 2. Cross-sectional heartwood area at the different *E. globulus* stem height levels in each site. Average of twelve trees per site.

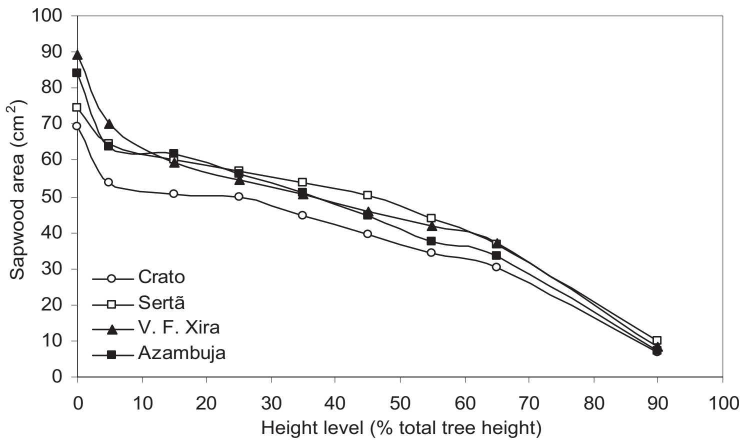

Figure 3. Cross-sectional sapwood area at the different *E. globulus* stem height levels in each site. Average of twelve trees per site.

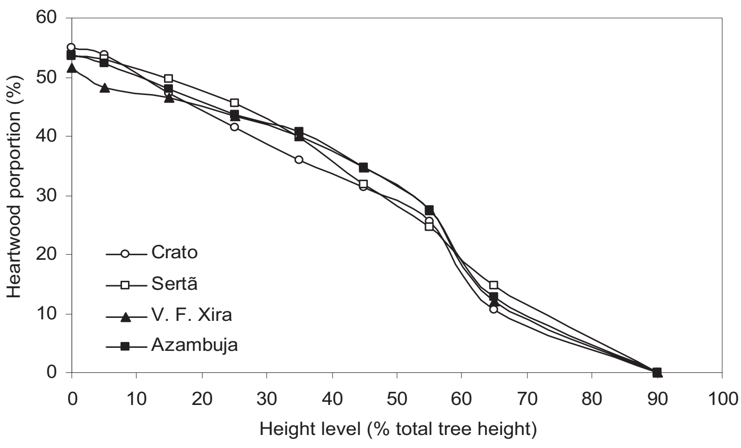

Figure 4. Mean relative heartwood area (%) in the cross-section at the different *E. globulus* stem height levels in each site. Average of twelve trees per site.

for V. F. Xira and Azambuja the relationship was highly significant with a determination coefficient below 78%. Using all the trees, the correlation between these variables is significant ($r = 0.72$, $P < 0.000$) but had determination coefficient value lower than those for V. F. Xira and Azambuja site.

4. DISCUSSION AND CONCLUSIONS

The *E. globulus* trees in the plantations in the four sites showed different mean annual growth in height and diameter (Tab. II) expressing the influence of site conditions and response to environmental variations [6,26]. The mean values of height growth were highest in Sertã (1.80 m y^{-1}) and lowest in Crato (1.36 m y^{-1}), while diameter growth was highest in Azambuja (1.19 cm y^{-1}) and lowest in Crato (0.88 cm y^{-1}). Within the site, the trees also showed differences in growth, especially in diameter, with coefficients of variation of the mean around 20% (Tab. II).

The extent and the pattern of the within-tree development of heartwood in these eucalypt trees are in general agreement

Table IV. Results from analysis of variance of the sites and variance components in percent of total (VC %) for the proportion of heartwood and the sapwood width.

	df	Crato		Sertã		V. F. Xira		Azambuja	
		Sign.	VC %	Sign.	VC %	Sign.	VC%	Sign.	VC%
Heartwood proportion (%)									
Trees (T)	11	***	8.6	***	7.4	***	4.9	***	5.5
Height levels (H)	8	***	85.5	***	87.2	***	88.1	***	88.0
H × T	88	***	5.8	***	5.4	***	6.9	***	6.4
Error			0.1		0.0		0.1		0.1
Sapwood width (cm)									
Trees (T)	11	***	26.3	***	35.2	***	53.6	***	59.6
Height levels (H)	8	***	31.4	***	25.2	***	17.6	***	15.9
H × T	88	***	41.9	***	39.3	***	28.5	***	24.1
Error			0.4		0.3		0.3		0.4

df: Degrees of freedom.
Sign. (Significances): n.s., not significant at 5% level; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

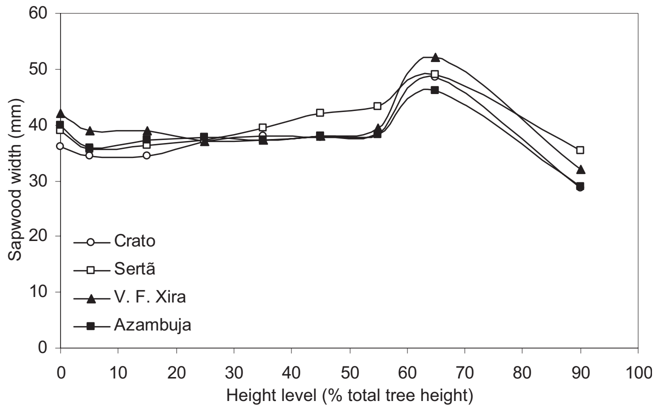

Figure 5. Sapwood width at the different *E. globulus* stem height levels in each site. Average of twelve trees per site.

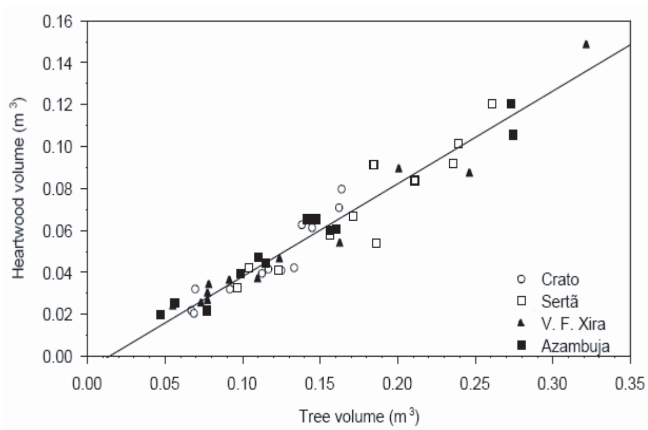

Figure 6. Heartwood volume (m^3) versus tree volume (m^3) for all the *E. globulus* trees in the four sites.

with previous reports for the species [8, 18]. In height heartwood stopped on average at 84.4% of total tree height, corresponding to heartwood stem heights ranging between 16.6 m

Table V. Models and correlation coefficients (r) for sapwood width and heartwood diameter (y), regressed on tree diameter (x).

	Site	Model	r
Heartwood diameter (cm)	Crato	$y = -2.577 + 0.921\ x$	0.93 ***
	Sertã	$y = -3.702 + 0.986\ x$	0.88 ***
	V. F. Xira	$y = -1.208 + 0.788\ x$	0.99 ***
	Azambuja	$y = -0.256 + 0.718\ x$	0.98 ***
Sapwood width (cm)	Crato	$y = 2.577 + 0.079\ x$	0.21 n. s.
	Sertã	$y = 1.959 + 0.133\ x$	0.46 n. s.
	V. F. Xira	$y = 1.208 + 0.212\ x$	0.87 ***
	Azambuja	$y = 0.257 + 0.282\ x$	0.88 ***

Significances: n.s., not significant at 5% level; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

and 22.0 m, and a heartwood-free stem length between 2.3 m and 3.6 m. (Tab. III).

The results published by Gominho and Pereira [8] for 9-year-old trees indicate that heartwood was present until 60–75% of total tree height and the heartwood-free stem had an average length of 5.3 m. They also found a linear regression for the heartwood height as a function of total tree height very similar to the model obtained here. With 18-year-old trees, Miranda et al. [18] reported that heartwood attained 62–73% of tree height with a 7.2 m heartwood-free stem.

The amount of heartwood decreased in the stem from the base upwards with a profile that followed rather closely the stem wood profile and was very similar for all the trees (Fig. 2). As a result from this type of development there was a slight decreasing variation of heartwood proportion in the stem cross-section (Fig. 4). No site effect was observed regarding this axial variation of heartwood proportion, while within-the-site there was a significant between-tree variation (Tab. IV). Such pattern of heartwood axial variation broadly parallels findings for *E. globulus* [8, 18] as well as for *E. grandis* [28], *E. tereticornis* [22], and the urograndis hybrid eucalypt [7]. This type of within-tree variation of heartwood is found in all the hardwood and softwood species that have been investigated [13] and derive from the process of heartwood

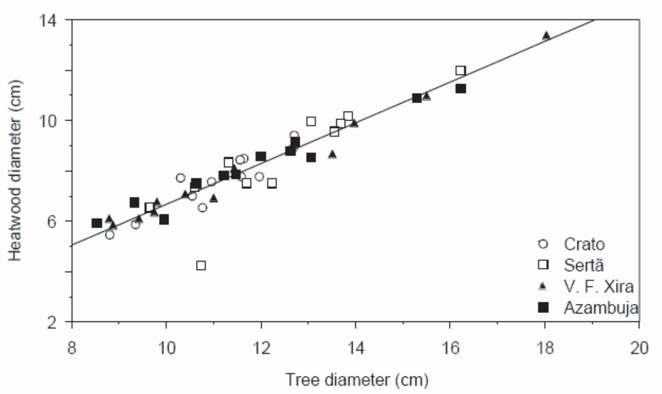

Figure 7. Relationship between heartwood diameter and tree diameter, at 15% height level on the *E. globulus* trees in the four sites.

formation that starts at a certain tree age and size and progresses outwards in the radial direction and upwards in the axial direction.

The average proportion of heartwood in the lower part of the stem was substantial, e.g. 54% of the cross-section at the 5% height level, values somewhat higher than the 42% found by Gominho and Pereira [8] for 9-year-old *E. globulus* trees, but lower than the 73% found by Miranda et al. [18] for 18-year-old *E. globulus* trees. This indicates the role of tree age in increasing the heartwood proportion as has been referred, too for *E. grandis* [2], *Populus tremuloides* [29], *Pseudotsuga menziesii* [13], *Abies balsamea* [11] and *Pinus pinaster* [21].

Heartwood represented 39% of the tree volume (Tab. III), a value also somewhat above the approximately one third of the total tree wood volume found previously for *E. globulus* [8] and *E. tereticornis* [22]. These values show that the proportion of heartwood in the trees used for pulping at the usual harvest age in temperate climates (9–14 years) is important and should be taken into account due to the negative impacts of heartwood on the pulpwood quality [20]. An increase of harvest age will increase the proportion of heartwood: for instance, in 18-year-old trees heartwood represented 60% of the total volume [18].

The sapwood had a mean radial width in the lower half of the tree of 38 mm (Fig. 5). Other studies on sapwood development have also reported an approximately constant width of sapwood along the below-the-crown stem for several other species (*Pinus contorta* [30], *P. pinaster* [14,21], *P. banksiana* [31], *Acacia melanoxylon* [15]). For *E. globulus*, sapwood radial width has been reported in the lower part of the stem with values in the range of 15 mm to 37 mm [9, 17, 18], while for *E. grandis* values between 9 mm and 48 mm were reported [28], and 25 mm to 50 mm for *E. maculata* [2].

The amount of sapwood in a tree is related to its conductive needs that are in relation with its crown development [24], and therefore the formation and development of heartwood progresses within the tree to regulate the amount of sapwood [1]. This explains the different distribution pattern of heartwood and sapwood within the stem and the positive relation of tree growth with heartwood content.

Heartwood content was found to be positively influenced by the tree growth: a linear relationship between heartwood volume and tree volume was obtained (Fig. 6), heartwood diameter and tree diameter showed a positive and highly significant correlation (Fig. 7 and Tab. V) and heartwood height was positively related with tree height (Fig. 1). There was no influence of site in heartwood content apart from the consequences induced in the different tree growth. Such influence of tree growth on heartwood has been referred to for eucalypts [8,9,17,28] and several other species (e.g. [3,14,21,27,29,30]).

On the contrary, the variation of sapwood width was not explained well by the tree diameter (Tab. V). This has earlier been reported by Wilkins [28] in *E. grandis*, although some other studies in *Pinus radiata* [4] and *E. grandis* [3] have found linear relationship of these two variables.

In conclusion, the results obtained showed that when harvested for the pulp industry *E. globulus* trees have a significant proportion of heartwood. The sapwood width is regulated by the formation of heartwood with a radial and axial development within the tree. Therefore the heartwood amount in the tree is positively related with tree size, and the factors that will result into a faster tree growth (e.g. site) will increase heartwood. The silvicultural management of *E. globulus* plantations used for pulping should take into account the presence of heartwood in the trees and the factors of its variation.

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