

VARIABILITY OF HEARTWOOD CONTENT IN PLANTATION-GROWN *EUCALYPTUS GLOBULUS* LABILL.

Jorge Gominho

Research Assistant

and

Helena Pereira†

Professor

Centro de Estudos Florestais
Instituto Superior de Agronomia
Universidade Técnica de Lisboa
1300 Lisboa Codex
Portugal

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ABSTRACT

The heartwood content in *Eucalyptus globulus* Labill. was studied in 9-year-old trees from commercial pulpwood plantations in three sites in Portugal. Heartwood was present in all the trees and attained 60–75% of total tree height and approximately one-third of the total volume. Within the tree, heartwood decreased from the base upwards, on average representing 40%, 31%, 22%, and 10% of the cross-sectional area at, respectively, 5%, 25%, 35%, and 55% of total tree height. The heartwood:sapwood ratio at each position within the tree depended highly significantly on site and on the tree. The axial development of heartwood also showed an interaction with site and tree. A positive correlation was found between heartwood content and growth. Considering its negative impact in pulping, the heartwood of *E. globulus* should be considered in management and breeding programs.

Keywords: Heartwood, sapwood, *Eucalyptus globulus* Labill., variability, growth.

INTRODUCTION

The formation of heartwood within the tree stem corresponds to the loss of conducting properties and to the accumulation to varying degrees of nonstructural compounds with protection, storage, or other purposes. The formation of heartwood is often clearly visible in the inner part of the stem cross-section by a distinct change of color.

Depending on end use, either sapwood or heartwood is favored. When the tree is used for pulping, heartwood is disadvantageous due to the higher content of extractives, which increase the consumption of pulping chemicals and the corrosion of equipment and reduce pulp yields and pulp brightness. Impregnation with pulping chemicals may also be more dif-

icult, thereby affecting delignification rates. These effects are in direct relation to the extent of extractive accumulation and their composition (Higgins 1984).

The ratio heartwood:sapwood varies with families, genera, and species (Hillis 1987). Other factors, such as silvicultural treatments (Wilkins 1991; Yang and Hazenberg 1991), tree age (Yang and Hazenberg 1991; Hazenberg and Yang 1991), or growing conditions (Wilkes 1984, 1991) and crown vitality (Kort 1993), may also affect the formation of heartwood. On the whole, however, heartwood formation has not been extensively studied, especially in relation to fast-grown plantation pulpwoods, nor the potential for using its variability in forest management and tree breeding.

In *Eucalyptus*, a strong relationship between

† Member of SWST

heartwood width and tree age has been reported, with the trees starting to form heartwood between 5 and 8 years (Hillis 1962, 1972, 1987). Several studies have considered *Eucalyptus grandis*, and heartwood has been found to be positively correlated to tree growth (Bamber and Fukazawa 1985). Heartwood formation has not been studied in *Eucalyptus globulus*, which is an important species for the production of high-quality bleached pulp and has been planted worldwide in short-rotation forestry systems. In Europe, it is the most important pulpwood species in the Iberian peninsula.

The objective of this work was to evaluate the heartwood content in plantation *Eucalyptus globulus* trees harvested after 9 years for pulp production and to give a first insight into the within- and between-tree variability of heartwood formation in this species.

MATERIAL AND METHODS

Heartwood in *Eucalyptus globulus* Labill. was studied in a total of 30 trees harvested at 9 years of age at the end of the first rotation, from commercial plantations in three different sites in Portugal. The plantations were established with seedlings from a commercial seed source planted at 3- × 3-m spacing. Site localization and climatic conditions (mean annual rainfall and temperature) are the following:

Chamusca [CH] 39°15'N, 0°42'W; 737 mm,
16.0°C
Penamacor [PE] 40°10'N, 7°10'W; 825 mm,
15.6°C
Odemira [OD] 37°40'N, 0°30'W; 606 mm,
16.1°C

In each site, two 100-tree plots were established, and diameter at breast height (dbh) was measured. Five trees were harvested per plot as follows: three trees with the mean plot dbh and two trees with the mean plot dbh plus and minus the standard deviation, respectively. Sampling was done on cross-sectional discs taken at different height levels: 5%, 25%,

35%, 55%, 65% of total tree height and at the top (corresponding to a 7-cm diameter).

The delimitation of heartwood was made visually by color difference, after some experimentation. In general, heartwood is easily recognized after harvesting by a darker shading, but this is quickly lost with drying. Staining recommended for heartwood coloring, such as IKI, NaNO₂, or FeCl₂ (10%) did not prove effective for *E. globulus*. Both water steaming and liquid water impregnation distinguished heartwood successfully, and the latter was used for operational simplicity. The heartwood and the disc area were measured using an image analysis system (Pereira et al. 1996). Three measurements were made on each disc.

The tree volume and the heartwood volume were calculated by sections corresponding to the different height levels of sampling, as conical sections (0–5%, 5–25%, . . . × 65% – top) and as cone (top) using the following equations, respectively:

$$V = \frac{h}{3}(s_a + s_b + \sqrt{s_a \times s_b}) \quad \text{and}$$

$$V = \frac{1}{3}s_c \times h \quad (1)$$

where s_a —area at the lower height level; s_b —area at the higher height level; s_c —area at the top; h —height of the section.

The sapwood volume was calculated by difference.

Analysis of variance and regressions were performed using the SAS procedures, and the 0.05 level was used in significance tests.

RESULTS AND DISCUSSION

Height of heartwood

The statistical data and analysis of variance for total tree height and for the height of heartwood within the tree are shown in Table 1 at site and plot levels. Tree growth was highly significantly different between sites, highest in Chamusca and lowest in Penamacor (21.1 m vs. 14.5 m) and within-site plot differences occurred only in Odemira. It is known that *E.*

TABLE 1. Statistical data for height of tree and of heartwood in 9-year-old *E. globulus* in three sites.

Site	Tree height, m						Heartwood height, m					
	Mean		Std.		S-N-K*		Mean		Std.		S-N-K*	
	Site	Plot	Site	Plot	Site	Plot	Site	Plot	Site	Plot	Site	Plot
[CH]	21.07	21.45	2.17	2.30	a	a	15.63	16.02	2.74	2.68	a	a
		20.70		2.23		a		15.25		3.05		a, c
[PE]	14.54	15.08	2.43	2.63	b	b	8.70	9.11	2.25	2.57	b	b
		14.00		2.37		b		8.30		2.10		b
[OD]	17.57	14.78	4.01	2.02	c	b	13.02	10.76	4.04	1.48	a	b, c
		20.36		3.55		c		15.28		4.68		a, c

* Student-Neuman-Keuls test, $\alpha = 0.05$. means with the same letter are not significantly different.

globulus growth responds to microenvironmental variation and, in some cases, plots within the same experimental design may show significant differences (Tomé and Pereira 1991).

The heartwood stopped at approximately 60% of total tree height in Penamacor and at 74% in Chamusca and Odemira. The height attained by heartwood in the tree showed a higher between-tree variability and more differences at plot level than total tree height.

A strong correlation was found between tree height and height of heartwood for these 9-year-old trees, corresponding to a linear model with $r = 0.95$ and $P < 0.000$ (Fig. 1):

$$H_{\text{heartwood}} = -5.43 + 1.00 H_{\text{total}} \quad (2)$$

This model predicts a heartwood-free tree height of 5.4 m. To estimate the age corresponding to this height, we used the distance-

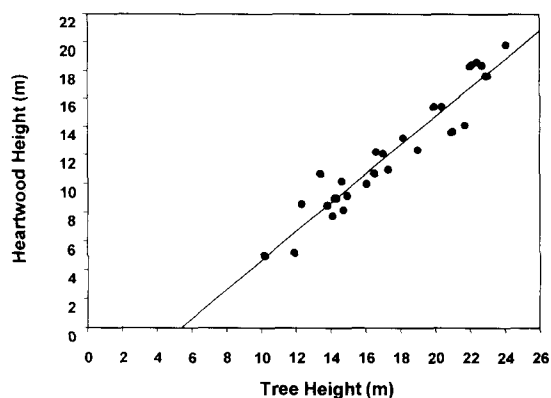


FIG. 1. Relation between height of heartwood and tree height of 9-year-old *E. globulus* trees.

independent individual tree models developed for *E. globulus* plantations to project tree height through the rotation age (Tomé and Pereira 1991). It was possible to estimate that the heartwood-free height at the top of the tree corresponds to approximately 4 years of tree growth. The formation of heartwood in *E. globulus* seems, therefore, to occur a little earlier than the 5–8 years reported for the beginning of heartwood formation in other *Eucalyptus* species (Hillis 1972, 1987). For *Populus tremuloides*, the transformation of sapwood into heartwood begins also at age 5 (Yang and Hazenberg 1991), but for plantation *Pinus radiata*, heartwood was detectable only when the tree was 12–15 years old (Wilkes 1991).

Considering the significant difference in height for the three sites, independent correlations with the height of heartwood were made for each site:

$$\begin{aligned} \text{[CH]} \quad H_{\text{heartwood}} &= -8.00 + 1.12H_{\text{total}} \\ r &= 0.88 \\ P &< 0.000 \end{aligned} \quad (3)$$

$$\begin{aligned} \text{[PE]} \quad H_{\text{heartwood}} &= -3.71 + 0.95H_{\text{total}} \\ r &= 0.96 \\ P &< 0.000 \end{aligned} \quad (4)$$

$$\begin{aligned} \text{[OD]} \quad H_{\text{heartwood}} &= -4.34 + 0.90H_{\text{total}} \\ r &= 0.93 \\ P &< 0.000 \end{aligned} \quad (5)$$

The corresponding heartwood-free tree

TABLE 2. Within-tree variation of heartwood and sapwood for the three sites. Mean of 10 trees and standard deviation.

	Height levels				
	5%	25%	35%	55%	65%
Heartwood area, cm ²					
[CH]	48.2 (18.4)	30.5 (11.5)	17.0 (9.6)	5.6 (6.4)	1.0 (1.1)
[PE]	32.8 (23.2)	13.9 (11.1)	5.9 (6.3)	0.6 (0.5)	0
[OD]	55.2 (24.1)	28.4 (23.2)	19.1 (12.9)	9.2 (14.4)	2.4 (3.6)
Sapwood area, cm ²					
[CH]	64.0 (22.6)	50.4 (19.2)	49.8 (17.0)	35.6 (11.2)	28.3 (9.1)
[PE]	55.0 (13.2)	45.3 (14.7)	39.3 (14.8)	24.2 (8.5)	17.2 (4.0)
[OD]	64.1 (20.8)	51.7 (23.2)	45.5 (21.9)	32.8 (14.9)	24.3 (11.6)
Heartwood : sapwood					
[CH]	0.77 (0.25)	0.64 (0.17)	0.37 (0.18)	0.16 (0.17)	0.04 (0.05)
[PE]	0.55 (0.30)	0.28 (0.18)	0.15 (0.14)	0.02 (0.02)	0
[OD]	0.87 (0.28)	0.55 (0.20)	0.43 (0.19)	0.23 (0.26)	0.08 (0.08)

heights are 7.1 m, 3.9 m, and 4.8 m, respectively, for [CH], [PE], and [OD], values that correspond with the difference in height growth of the trees in these sites. The estimates of tree age corresponding to these heights made individually for each site also confirm the approximate value of 4 years for the beginning of heartwood formation. It should be noted, however, that the calculations estimated 3–4 years for Penamacor and Odemira and 4–5 years for Chamusca. The assumptions made for the age projections do not allow accurate estimates, and these values should be taken only as indicative. However, the possibility of a later formation of heartwood in trees with the highest growth (as the data obtained for Chamusca suggest) might be of interest for further research.

Heartwood content

Within the tree, the heartwood area at each height level decreased always from the base upwards (Table 2). Heartwood represented on average 40% of the total cross-sectional area at the base, 31% and 22% at the 25% and 35% height levels, and only 10% at the 55% height level. There was an important between-tree variability within each site, with coefficients of variation of the mean usually above 50%, especially for the higher positions in the stem. Differences between sites were found for total

heartwood and sapwood areas, as a result of a higher radial growth in Chamusca and lower in Penamacor, as already observed for height growth (Table 1).

The heartwood distribution in the tree is shown in Fig. 2 as site average, represented as the mean for each height level. Wilkins (1991) also reported a similar pattern of within-tree distribution of heartwood in 9.5-year-old *E. grandis*, with heartwood decreasing with height from ca. 45–55% to 35–45% at 25% and 50% height levels, respectively.

Differences in the heartwood : sapwood ratio along the stem occurred both between trees in the same site and between sites. It is noteworthy that in Penamacor, where growth was less, relatively less heartwood was formed at each height level and that it stopped at a lower height level in the tree (Table 2). This is in agreement with the results obtained for *E. grandis* where percentage of heartwood was greater in trees with faster growth (Wilkins 1991), as well as with similar results obtained for *P. radiata* (Harris 1954; Hillis and Ditchburne 1974). However, some authors report an inverse correlation in other species, i.e., heartwood content being negatively correlated to growth (Karkkainen 1972; Hillis 1987).

The variability of heartwood content was studied using as a variable the heartwood : sapwood ratio, measured for all trees at the dif-

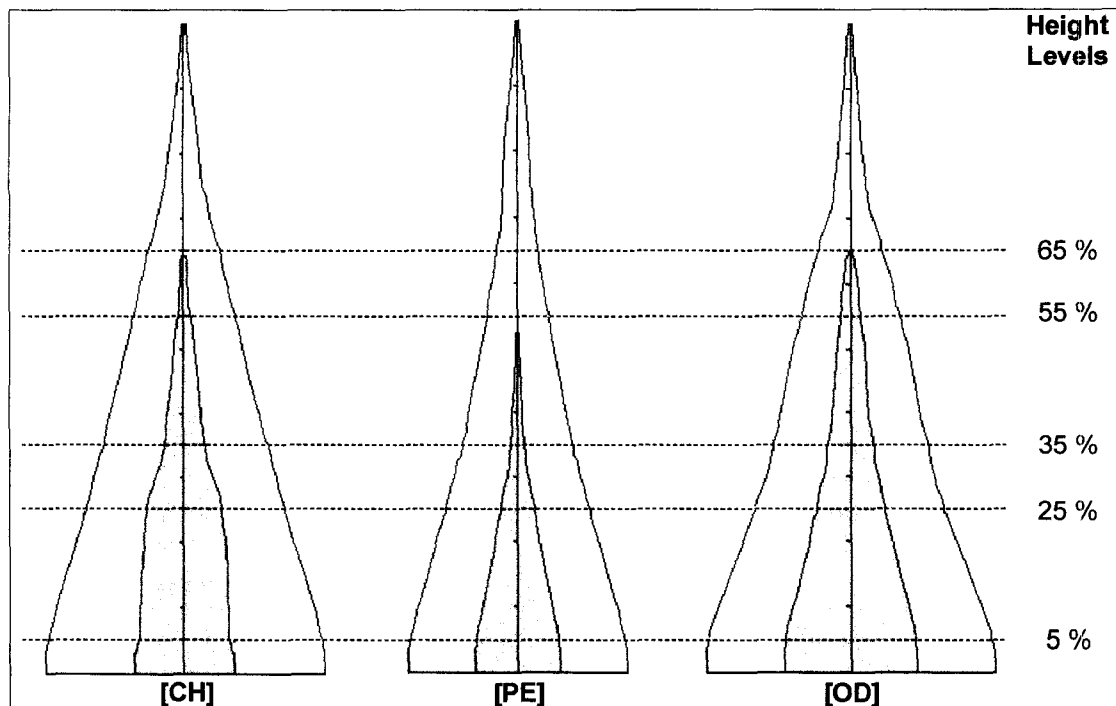


FIG. 2. Distribution of heartwood within the stem of *Eucalyptus globulus* for three sites. Mean of 10 trees per site.

ferent height levels (Table 3). Highly significant sources of variation were the position along the tree (i.e., the axial development of heartwood), the tree and the interaction tree \times height level. Site and site \times height level interactions are also very significant sources of variation, but the plot within a site was not significant. The decomposition of the variance by sources of variation showed that the major part of variation results from the position in the tree and its interaction with the tree (59% and 19% of total variation, respectively), with

site and tree explaining, respectively 8% and 9% (Table 3).

The between-tree comparison of heartwood content at one height level, e.g., at 25% of total tree height, which is a common sampling height for wood quality evaluation in *E. globulus* (Table 4), shows that the site and the tree are similar sources of the total variation.

Heartwood volume

The same types of results are obtained if volumes are calculated for the tree and for the

TABLE 3. Analysis of variance for the heartwood : sapwood ratio in 9-year-old *E. globulus* trees.

Source of variation	df	MSE	P-value	Variance component	Percent of total
Site	2	1.960	0.002**	107.7	7.9
Plot (Site)	3	0.021	0.958 ns	0.0	0.0
Tree (Plot Site)	24	0.214	0.000***	118.2	8.7
Level	5	7.266	0.000***	803.5	59.3
Site \times Level	10	0.189	0.001**	51.9	3.8
Plot \times Level	15	0.339	0.966 ns	0.0	0.0
Tree \times Level	120	0.078	0.000***	256.2	18.9
Error		0.018		18.3	1.3

TABLE 4. Analysis of variance for the heartwood : sapwood ratio of 9-year-old *E. globulus* trees at 25% of total tree height.

Source of variation	df	MSE	P-value	Variance component	Percent of total
Site	2	1.035	0.016*	329.6	46.5
Plot (Site)	3	0.041	0.727 ns	0.0	0
Tree (Plot Site)	24	0.107	0.000***	346.6	48.9
Error		0.003		33.3	4.7

heartwood. The average heartwood volumes for the three sites were, respectively, 0.033, 0.010, and 0.027 m³ for [CH], [PE], and [OD], corresponding to 30%, 17%, and 26% of total tree volume. Heartwood represented the smallest tree fraction in the site with the slowest growth [PE] and the largest for the better site [CH].

Considering the pooled individual values for the trees, the heartwood volume was strongly correlated with tree volume (Fig. 3), corresponding to a linear regression:

$$V_{\text{heartwood}} = -0.0057 + 0.3376V_{\text{total}}$$

$$r = 0.96 \quad P < 0.000. \quad (6)$$

On average, heartwood volume corresponds approximately to one-third of the total tree wood volume. The tree is a highly significant source of variation accounting for 45% of the total variance, with site as a significant source (33% of total variance) (Table 5). It is note-

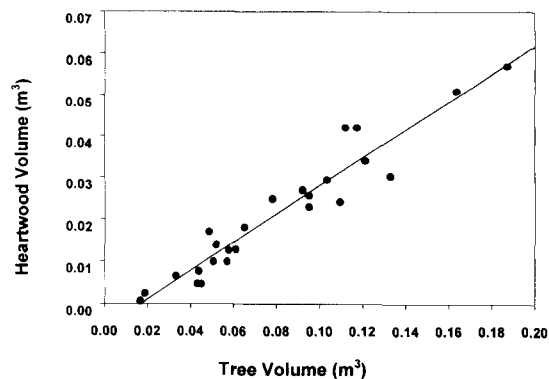


FIG. 3. Relation between heartwood volume and total tree volume of 9-year-old *E. globulus* trees.

TABLE 5. Analysis of variance for the heartwood volume percentage of 9-year-old *E. globulus* trees.

Source of variation	df	MSE	P-value	Variance component	Percent of total
Site	2	1595.2	0.050*	147.5	32.7
Plot (Site)	3	168.6	0.540 ns	0.0	0.0
Tree (Plot Site)	24	228.6	0.000**	65.5	45.1
Error		31.9		31.9	22.0

worthy that the percentage of heartwood in relation to tree volume has a high between-tree variability ranging approximately 5% to 45% as a result of the combined variability of heartwood : sapwood ratio at each height level and tree growth (Fig. 4). However, there is a trend of increasing heartwood volume content with tree volume ($P = 0.002$) in agreement with the reported results of a positive correlation of heartwood content and growth for *E. grandis* (Wilkins 1991).

The results obtained suggest that heartwood should be taken into consideration for the evaluation of pulpwood quality of young plantation grown *E. globulus*. Site differences point to the probable influence of environment and growth on heartwood formation. On the other side, the high between-tree variability both on total heartwood content and on its axial development also suggests a possible genetic influence and the interest of its assessment as a potential selection trait in breeding programs.

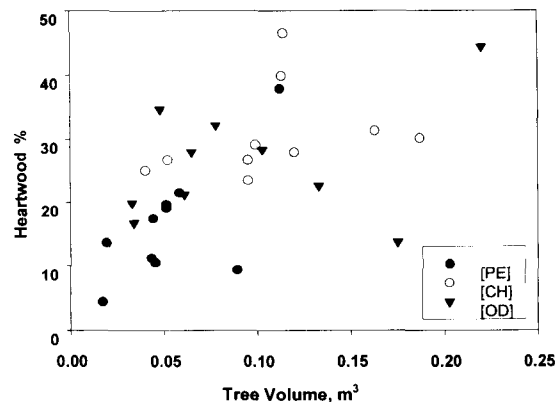


FIG. 4. Heartwood volume percentage and total tree volume of 9-year-old *E. globulus* trees in the three sites.

CONCLUSIONS

Heartwood was found in all the plantation-grown 9-year-old *Eucalyptus globulus* trees studied, where it attained 60–75% of total tree height and corresponded to approximately one-third of the tree volume. There was a positive correlation of heartwood content and growth. Within the tree, heartwood decreased from the base upwards, and this axial development of heartwood showed an interaction with site and tree. At each position within the tree, the heartwood:sapwood ratio depended highly significantly on site and on the tree. The variability found suggests the consideration of heartwood content for *E. globulus* wood quality evaluation in management and breeding programs.

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