THE INFLUENCE OF TREE SPACING IN HEARTWOOD CONTENT IN *EUCALYPTUS GLOBULUS* LABILL.

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ABSTRACT

Heartwood content was studied in 27 *Eucalyptus globulus* Labill. trees with spacings 3 × 3, 3 × 2, and 2 × 1 (m × m), with 9 years, from a 1st rotation spacing trial. The height attained by heartwood increased with total tree height independently of spacing, and reached on average 45%, 59%, and 62% of total height, respectively, for spacings 2 × 1, 3 × 2, and 3 × 3. In all the spacings, the heartwood radius decreased gradually along tree height, and the radial thickness of sapwood remained practically constant at approximately 16 mm in the lower part of the stem (<35% of height), and increased upwards. Sapwood thickness did not depend on tree growth rate, remaining constant for all tree diameters. Heartwood diameter increased with tree diameter, with larger trees showing more heartwood regardless of spacing. Sapwood thickness was not correlated with tree radius, but sapwood area showed a good linear regression. The proportion of heartwood volume increased with spacing from 20.3% to 41.1% of tree volume, respectively for 2 × 1 and 3 × 3 spacings.

Keywords: *Eucalyptus globulus* Labill, heartwood, sapwood, spacing, variability.

INTRODUCTION

Heartwood is the physiologically inactive central part of tree stems where cells accumulate extractives in variable, and sometimes large, amounts. A few reviews have been published on heartwood formation and characteristics (Bamber and Fukazawa 1985; Hillis 1987; Taylor et al. 2002). The increased content of extractives, mostly dark-colored and of phenolic nature, impacts negatively on the chemical pulping of wood, e.g. more consumption of chemicals, lower pulp yields, and reduced pulp brightness (Higgins 1984), and on the paper manufacturing, e.g. sticking at the press, color change, and wettability problems (Hillis 1962).

The formation of heartwood also induces anatomical changes related to pit aspiration and tylose development that reduce diffusion of liquids, thereby imparting slower impregnation of wood in the pulping reactor (Womeldorff 1965).

The presence of heartwood therefore reduces the wood assortment quality at the pulp mill. However, little attention has been given to heartwood when evaluating raw material quality, both in tree breeding for increasing wood volume and quality and in plantation management practices of pulpwood species.

Some eucalypt species are used extensively in plantations, accounting for 10% of the estimated 187 million ha of the world forest plantations (FAO 2001). The eucalypt plantations are managed intensively in short rotation cycles, mostly directed for pulpwood production. The blue gum eucalypt (*Eucalyptus globulus*) was one of the first to be used in plantations for pulp production, combining fast tree growth with excellent wood properties for printing quality bleached pulp production.

In *Eucalyptus*, trees start to form heartwood between 5 and 8 years (Hillis 1972, 1987) or earlier (Hillis 1962). In commercial pulpwood plantations, *E. globulus* trees at the harvest age of 9 years contained heartwood up to 60–75% of tree height and amounting to 17–30% of tree volume (Gominho and Pereira 2000). In the eucalypt hybrid urograndis (*E. grandis* × *E. urophylla)*, heartwood amounted to 39% of the volume in 6-year-old trees (Gominho et al. 2001). Heartwood proportion was positively correlated with tree growth in *E. grandis* (Bamber and Fukazawa 1985), *E. globulus* (Gominho and Pereira 2000), and *E. tereticornis* (Purkayastha et al. 1980).

Plantation spacing is known to influence *E. globulus* growth, with larger volumes per hectare associated to closer spacings and larger tree diameters to wider spacings (Tomé et al. 1995; Delgado and Tomé 1997), but its influence on heartwood development has not been studied. The objective of this work is to evaluate the heartwood and sapwood content and their variation in *Eucalyptus globulus* trees planted with different spacings at the pulp production harvest age of 9 years.

MATERIAL AND METHODS

Heartwood was studied in *Eucalyptus globulus* Labill. trees harvested at 8.8 years of age, at the end of the 1st rotation, from a spacing trial established with seedlings from a commercial seed source. The trial area belongs to StoraEnso and was established in April 1990, in Quinta do Paço (41º35'N, 0º43'W), near to Braga, North of Portugal, 25 km from the Atlantic Ocean and at an elevation of 160 m. The climate is Atlantic with a moderate Mediterranean influence with 1600–1800 mm annual rainfall, 12.5–15.0 ºC mean temperature, and 30–40 days of frost.

The trial area consists of two blocks each with five plots of different spacings (m × m): 2 × 1, 2 × 2, 3 × 1, 3 × 2, 3 × 3 and was regularly measured over time (Soares 1999). Only one block was harvested in January 1999, and the plots with spacings 2 × 1, 3 × 2, and 3 × 3 were used for tree sampling. The tree biometric data from the spacing plots used for sampling are given in Table 1 (Soares 1999).

In each spacing plot, nine trees were harvested as follows: the trees in the plot were divided into three diameter at breast height (dbh) classes of variable amplitude and constant frequency, and three trees per class were randomly selected. Sampling was made as cross-sectional disks taken at different height levels: 5%, 25%, 35%, 55%, and 65% of total tree height, and at the top (corresponding to a 7-cm diameter).

The delineation of heartwood was made visually by color difference, after water impregnation (Gominho and Pereira 2000) because the transition between sapwood and heartwood is not visible in some cases. The *E. globulus* Labill. has the same border dry and wet. The heartwood and the disk area were measured using an image analysis system (Pereira et al. 1996). Three measurements were made on each disk.

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 a cone (top) (Gominho and Pereira 2000). The sapwood volume was calculated by difference.

The height attained by heartwood was calculated for each tree as the intercept of the linear

TABLE 1. *Plot biometric data from 9-year-old* E. globulus *in the spacing trial used for tree sampling*

	Spacing (m × m)		
	2 × 1	3 × 2	3 × 3
Average height (m)	20.2	22.0	23.8
Average b.h. diameter with bark (cm)	10.1	14.5	16.2
Height to live crown base (m)	16.1	16.9	15.9
Crown length* (m)	4.1	5.1	7.9
Crown ratio**	0.19	0.23	0.32
Leaf area (m^2)	6.1	16.7	25.0

* Total height—height to live crown base.

** Crown length/height to live crown base.

TABLE 2. *Tree and heartwood height of 9-year-old* Eucalyptus globulus *grown with three spacings. Average of nine trees, standard deviation and SNK comparison test of means.*

Spacing	Tree height (m)	S-N-K	Heartwood height (m)	S-N-K	Heartwood % of tree height	S-N-K
[2 × 1]	17.7 ± 4.9	a	8.9 ± 6.2*	a	45.2 ± 15.4	a
[3 × 2]	21.1 ± 3.7	b	12.9 ± 5.2	b	59.4 ± 11.3	b
[3 × 3]	21.2 ± 3.4	b	13.3 ± 3.3	b	61.8 ± 10.3	b

* Two trees had no heartwood.
S-N-K; Student Newman Keuls test, $\alpha = 0.05$, means with the same letters are not significantly different.

regression of heartwood cross-section areas with height levels.

Statistical analysis was performed using SAS procedures, and the 0.05 level was used in significance tests. Analysis of variance was made considering spacing, tree and height level as fixed effects, as well as their interactions. Decomposition of variance into the different effects was made according to Montgomery (1991).

RESULTS

Heartwood height

Heartwood was present in all the trees from spacings 3 × 3 and 3 × 2, while in spacing 2 × 1 the two shortest trees showed no heartwood. Within the tree, heartwood reached on average 45%, 59%, and 62% of total height, respectively, for spacings 2 × 1, 3 × 2, and 3 × 3. The disk taken at the top of the trees never contained heartwood. A comparative test of means of tree and heartwood height (Student-Newman-Keuls) showed that only the spacing 2 × 1 was different from the other two spacings (Table 2).

The height attained by heartwood increased with total tree height, independently of spacing, and a strong correlation was found between tree height (in m) and height of heartwood (in m), corresponding to a linear model (Fig. 1):

$$H_{heartwood} = -10.97 + 1.13\ H_{total} \quad (\text{adj. } R^2 = 0.82,\ P < 0.000)$$

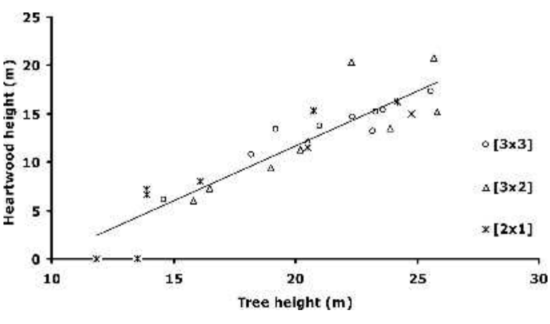

FIG. 1. Relation between height of heartwood and tree height of *E. globulus* trees grown with three spacings.

According to this model, heartwood will start when the tree attains 9.7 m of height and will increase axially at a rate higher than tree growth (1.1 m of heartwood per m tree height increase).

Heartwood area and proportion

The heartwood area in the stem cross-section decreased always from the tree base upwards (Fig. 2). At the same height level, the average heartwood area increased with spacing, but the range of values is wide within each case.

The proportion of heartwood in the cross-section decreased sharply with tree height, being very small at the highest height level (Table 3). At the same height level, the heartwood:sapwood area ratio was higher in the trees from the 3 × 3 spacing and decreased for the closer spacings, e.g. 1.07 and 0.52 at 25% height level, respectively, for the 3 × 3 and 2 × 1 spacings.

An analysis of variance of the heartwood:sapwood ratio demonstrated that all the factors considered (spacing, tree, height level, and their interactions) were highly or very highly significant sources of variation with height level as the main source of variation, accounting for 44.6% of the total (Table 4). The between-tree variation and the individual within-tree variation accounted, respectively for 20.6% and 18.4% of the total variation.

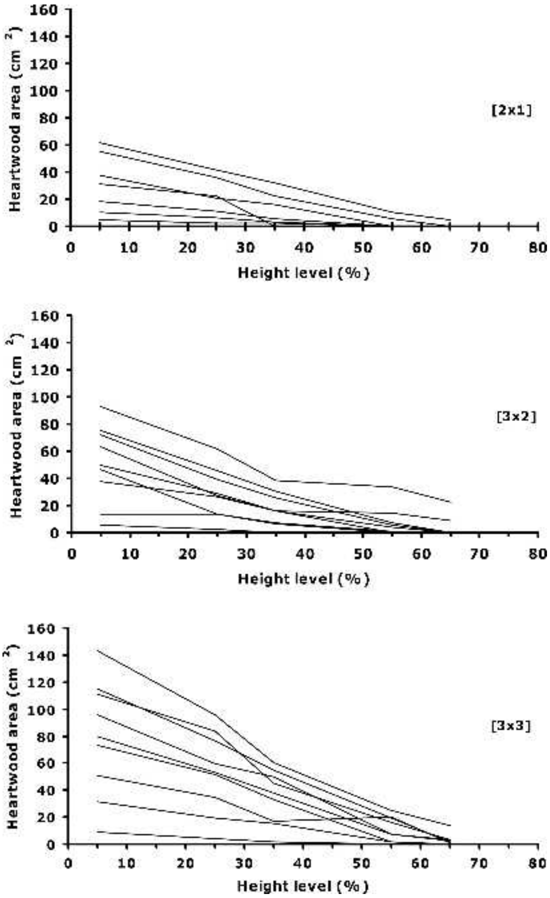

FIG. 2. Development of heartwood cross-sectional area with tree height in individual *E. globulus* trees grown with spacings 2 × 1, 3 × 2, and 3 × 3.

Radial width of sapwood and heartwood

The variation of the radial width of sapwood and heartwood at the different height levels is given in Table 5.

In all the spacings, the heartwood diameter decreased gradually along tree height. For instance, in spacing 3 × 2, heartwood diameter decreased from 76 mm to 10 mm between 5% and 65% of tree height, respectively. Between spacings, heartwood diameter decreased with increasing tree spacing, e.g. 96 mm, 76 mm, and 46 mm for spacings 3 × 3, 3 × 2, and 2 × 1, respectively, at 5% of tree height. In all cases, an important between-tree variation of heartwood diameter was present, expressed by coefficients of variation of the mean in general near or above 40%.

Regardless of the spacing, the radial thickness of sapwood remained virtually constant at approximately 16 mm in the lower part of the stem, until 35% of total tree height, increasing upwards at 55% and 65% height levels, respectively, to 21.0 mm and 22.5 mm (Fig. 3). The between-tree variation was small in the lower part of the stem and higher in the upper levels, as seen by the corresponding coefficients of variation of the mean, e.g. below 20% and around 30%, respectively.

An analysis of variance showed that spacing was not a statistically significant source of variation of sapwood width, while tree, height level, and their interaction were highly significant sources of variation (Table 6).

Effect of growth on sapwood and heartwood

In the lower part of the stem, the sapwood thickness did not depend on tree growth rate, remaining rather constant regardless of tree diameter (Fig. 4). The dispersion of values increased with tree height, and at the upper level there was a trend of increasing sapwood thickness with tree diameter.

Heartwood diameter increased with tree diameter, with larger trees showing more heartwood

TABLE 3. *Variation of the heartwood-to-sapwood ratio of cross-sectional area at the different tree height levels for* E. globulus *grown with three spacings. Mean of nine trees and standard deviation.*

	Height levels				
	5%	25%	35%	55%	65%
[3 × 3]	1.36 ± 0.43	1.07 ± 0.40	0.76 ± 0.31	0.31 ± 0.33	0.07 ± 0.11
[3 × 2]	1.08 ± 0.47	0.70 ± 0.29	0.44 ± 0.24	0.28 ± 0.47	0.17 ± 0.39
[2 × 1]	0.59 ± 0.41	0.52 ± 0.37	0.30 ± 0.29	0.05 ± 0.01	0.02 ± 0.05

TABLE 4. *Analysis of variance for the heartwood-to-sapwood ratio of cross-sectional areas in* E. globulus *trees.*

Source of variation	df	MSE	P-value	Variance component	Percent of total
Spacing	2	5.9635	**	0.0367	11.2
Tree (spacing)	24	1.0073	***	0.0671	20.6
Height level	4	11.9811	***	0.1457	44.6
Spacing × height level	8	0.6223	**	0.0164	5.0
Tree × height level	96	0.1806	***	0.0599	18.4
Error	270			0.0007	0.2

** ($P < 0.01$), ***($P < 0.001$).

TABLE 5. *Variation of sapwood and heartwood radial width at the different tree height levels in* E. globulus *trees grown with three spacings. Mean of nine trees and standard deviation.*

	Height levels				
(mm)	5%	25%	35%	55%	65%
Heartwood radius					
[3 × 3]	47.7 ± 16.0	38.9 ± 13.9	31.4 ± 11.9	16.0 ± 9.8	6.9 ± 6.7
[3 × 2]	38.1 ± 13.4	28.4 ± 10.8	21.2 ± 10.5	10.9 ± 11.2	4.8 ± 9.8
[2 × 1]	23.1 ± 16.5	18.3 ± 13.5	12.6 ± 12.2	3.6 ± 7.1	1.4 ± 4.1
Sapwood thickness					
[3 × 3]	14.8 ± 1.6	15.0 ± 1.9	16.1 ± 1.9	21.2 ± 6.0	26.1 ± 5.9
[3 × 2]	15.0 ± 2.0	16.5 ± 3.1	18.9 ± 4.2	21.1 ± 6.1	22.0 ± 7.2
[2 × 1]	16.7 ± 3.7	14.7 ± 3.5	17.4 ± 6.8	20.7 ± 5.6	19.6 ± 6.4

regardless of spacing. This trend was found at all height levels and is exemplified for the 5% height level in Fig. 4. When considering the first height levels (5%, 25%, and 35%), a quadratic model could be adjusted to the values of heartwood and tree diameter (Fig. 5):

$$D_{hearttwood} = 0.0012{D^2}_{total} + 0.7368D_{total} - 19.3996 \quad (\text{adj. } R^2 = 0.95, P < 0.000)$$

Sapwood thickness was not correlated with tree diameter, but sapwood area (in cm^2) showed a good linear regression with tree diameter (in cm):

$$Area_{sapwood} = 0.52D_{total} - 9.77 \quad (\text{adj. } R^2 = 0.87, P < 0.000).$$

The proportion of heartwood in the cross-section was found to depend on tree diameter, being higher for large trees. In Fig. 6, the variation of heartwood:sapwood area ratio at 25% of height level shows a clear increasing trend (adj. $R^2 = 0.46$, $P < 0.000$) with tree diameter.

Heartwood and sapwood volumes

The average tree volume increased with spacing, as did the average heartwood and sapwood volumes (Table 7). The proportion of heartwood within the tree volume also increased with spacing from 20.3% to 41.1% of tree volume, respectively, for the 2 × 1 and 3 × 3 spacings. Between-tree variability of the heartwood volume proportion was large in the closer 2 × 1 spacing, resulting largely from the fact that two trees did not contain heartwood. Calculation of stand volumes showed 259 m^3ha^{-1}, 154 m^3ha^{-1}, and 145 m^3ha^{-1}, respectively for the 2 × 1, 3 × 2 and 3 × 3 spacings, corresponding to 173 m^3ha^{-1}, 100 m^3ha^{-1}, and 79 m^3ha^{-1} of sapwood and 85 m^3ha^{-1}, 54 m^3ha^{-1}, and 65 m^3ha^{-1} of heartwood.

Heartwood volume was positively correlated with the tree volume ($r = 0.983$, $p < 0.001$). A polynomial regression model between the squared root of heartwood volume (in dm^3) and the tree volume (in dm^3).

$$\sqrt{V_{heartwood}} = 0.0001\ {V^2}_{total} + 0.0725\ V_{total} + 0.22 \quad (\text{adj. } R^2 = 0.97, P < 0.000)$$

was found to be the best fit (Fig. 7).

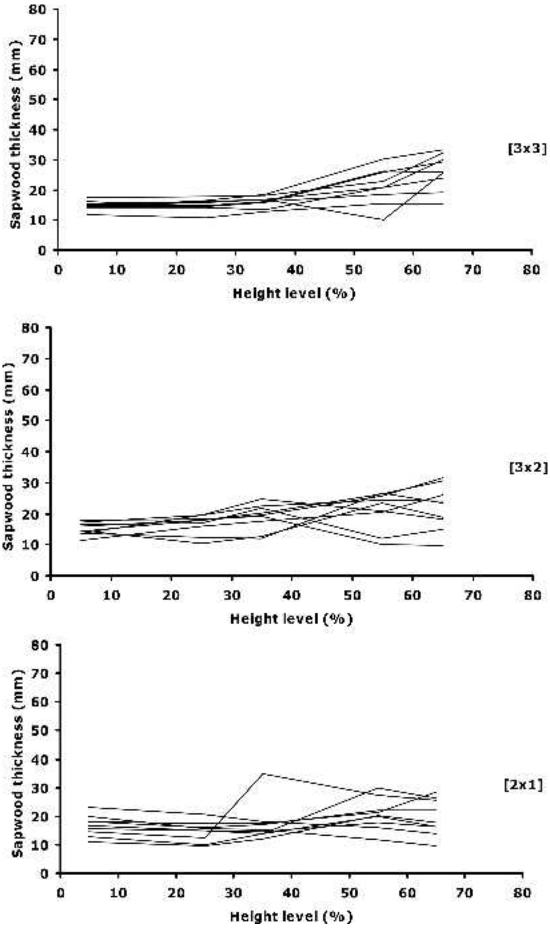

FIG. 3. Development of sapwood radial thickness with tree height in individual trees of spacings 2 × 1, 3 × 2, and 3 × 3.

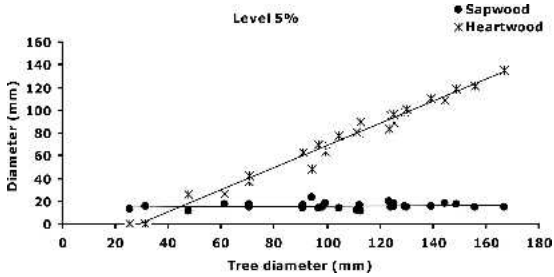

FIG. 4. Variation of heartwood diameter and sapwood thickness with total tree diameter in cross-section at 5% height level.

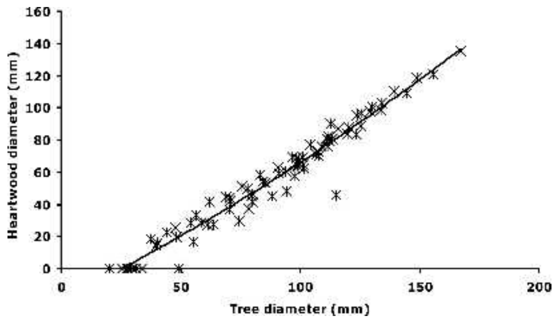

FIG. 5. Regression between heartwood diameter and tree diameter (levels 5%, 25%, and 35%) for all the *E. globulus* trees from the three spacings.

DISCUSSION

In the spacing trial where the sampling was done, an increase in tree spacing resulted in shorter and thinner trees with a smaller canopy (Table 1) resulting in a decrease of the average stem volume (Table 7). In terms of volume per hectare, the highest value was found for the closer spacing (259 m^3ha^{-1} *vs.* 145 m^3ha^{-1}, respectively, for the 2 × 1 and 3 × 3 spacing). A similar response of *E. globulus* to tree spacing has been reported previously (Soares 1995; Delgado and Tomé 1997).

It has been reported that heartwood formation is under a strong genetic control, though its initiation age can be influenced by environment

TABLE 6. *Analysis of variance for the sapwood thickness in* E. globulus *trees.*

Source of variation	df	MSE	P-value	Variance component	Percent of total
Spacing	2	30.7929	ns	0.1666	0.0
Tree (spacing)	24	124.6806	***	8.3040	21.8
Height level	4	854.8227	***	10.3258	25.9
Spacing × height level	8	92.3531	ns	2.7379	3.6
Tree × height level	96	55.4096	***	18.4297	48.4
Error	270			0.1205	0.3

ns, not significant, ***($P < 0.001$).

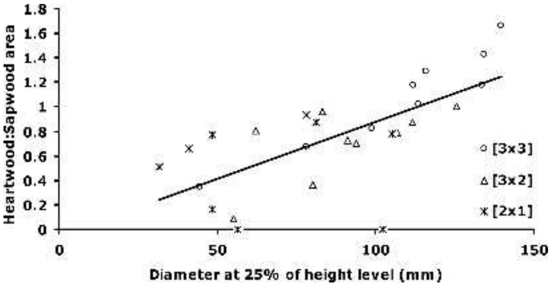

FIG. 6. Regression between heartwood:sapwood area ratio and diameter at 25% of height level for all the *E. globulus* trees from the three spacings.

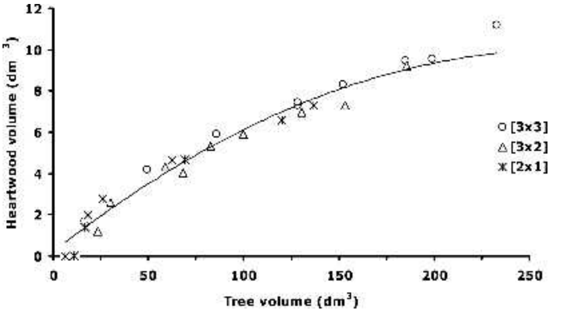

FIG. 7. Regression between the squared root of heartwood volume and tree volume for all the *E. globulus* trees from the three spacings.

and forest practices (Hillis 1987). In this study, spacing was the silvicultural effect that was analyzed. The differences in tree spacing clearly influenced individual tree biometry (Table 1) as well as stand volumes (Table 7). When comparing tree averages for each spacing, it was found that the heartwood development parameters showed an increase from spacing 2 × 1 to spacing 3 × 1, in relation to heartwood height (Table 2), heartwood-to-sapwood area ratio (Table 3), and heartwood volume proportion (Table 7). However, the spacing effect accounts for only a small part of the total variation (see Table 4); and it is the tree dimension that determines the extent of heartwood proportion within the stem, as discussed below.

The within-tree development of heartwood showed in the studied *E. globulus* trees the characteristic pattern of decreasing cross-sectional area (Fig. 2) and relative content (Table 3) from base upwards regardless of spacing. The same pattern has been described for many species (Hillis 1987), including *E. grandis* (Wilkins 1991), *E. tereticornis* (Purkayastha et al. 1980), the hybrid urograndis (Gominho et al. 2001), and specifically for *E. globulus* of a similar age (Gominho and Pereira 2000).

An estimation of cambial age for heartwood initiation was made from the within-tree height development of heartwood. The fact that in *E. globulus* annual rings are not distinct does not allow using ring analysis to calculate the age of heartwood initiation or its formation rate, as it is done e.g. for pine species (Mörling and Valinger 1999; Climent et al. 2003; Pinto et al. 2003). A model of heartwood height in function of tree height (Fig. 1) could be derived with very high statistical significance and a 0.82 correlation factor allowing estimating initiation of heartwood at 9.7 m. The trial was regularly measured along time, and this average tree height was attained at ages between 2.6 years (in spacings 3 × 2 and 3 × 3) and 3.6 years (in spacing 2 × 1) (Soares 1995). A previous estimation of heartwood initiation of 4 years was done for *E. globulus* plantations at 3 × 3 spacing using tree height equations (Gominho and Pereira 2000). Hillis (1962) has previously referred an age range for the beginning of heartwood formation in euca-

TABLE 7. *Average tree, heartwood and sapwood volumes (range of values in parenthesis) and heartwood volume percentage for 9-year-old* E. globulus *grown with three spacings.*

Spacing	Wood volume (dm^3) Mean (min. – max.) Total	Heartwood	Sapwood	Heartwood (% of total*)
[2 × 1]	51.7 (6 – 136)	16.1 (0 – 53)	35.6 (0 – 83)	20.3 ± 14.6
[3 × 2]	92.4 (23 – 186)	33.2 (2 – 85)	59.2 (21 – 101)	30.5 ± 12.5
[3 × 3]	130.8 (17 – 233)	59.9 (3 – 125)	70.9 (14 – 108)	41.1 ± 10.9

* Mean and standard deviation.

lypts between 2 and 6 years. Although the heartwood-free top tree length cannot be converted directly into tree age for heartwood initiation, this allows situating the probable beginning of heartwood development in trees growing in these conditions at 3–4 years.

However, tree age is not the only factor involved in heartwood formation and tree dimension; both diameter and height also have a determining role. In fact, the shortest trees in the sampling (two trees from the spacing 2 × 1, with 11.8–13.5 m and 4.7–5.9 cm b.h. diameter) contained no heartwood.

The proportion of heartwood in the stem cross-section increased with tree diameter, i.e. as shown for the 25% height level (Fig. 6). When analyzing the causes for the variation of the heartwood-to-sapwood area ratio by analysis of variance (Table 4), it was found that the tree is a highly significant effect and explains the largest share of the total variation, once the within-tree variation is accounted for.

The influence of tree growth rate and size in heartwood formation has been contradictorily reported in the literature. Some authors have referred negative correlations between heartwood content and tree growth (Kärkkäinen 1972; Hillis 1987), but positive correlations have been found for *Pinus radiata* (Wilkes 1991), *P. pinaster* (Pinto et al. 2003), and *Eucalyptus grandis* (Wilkins 1991). The same was reported for *E. globulus* (Gominho and Pereira 2000) and again confirmed in the present study.

It has been suggested that heartwood formation serves to regulate the amount of sapwood to a physiological optimum level (Bamber 1976), and therefore to tree growth. This agrees with the results obtained in this study for the sapwood variation.

The within-tree variation of sapwood clearly differed from that of heartwood (Fig. 4). The radial width of sapwood remained constant at approximately 1.6 cm in the lower part of the stems, regardless of tree dimensions (Table 5) but increased in the upper part of the stem (55% and 65% of stem height) and showed between-tree variation (Fig. 3). Average sapwood width in the upper part of the stem increased from spacing 2 × 1 to spacing 3 × 3, following the increase in crown dimensions and leaf area, e.g. at 65% height level, 2.0 cm and 2.6 cm in spacings 2 × 1 and 3 × 3, respectively, where crown ratio was 0.19 and 0.32 and leaf area 6.1 and 25.0 m^2 (Table 1). However, after this initial adjustment to the specific tree conditions, heartwood formation proceeded in order to maintain a constant and between-tree similar radial sapwood width, corresponding to an increasing sapwood area with tree diameter. This is in accordance with the fact that the within-tree development of heartwood in the lower part of the stem was correlated with tree growth, showing therefore a higher proportion in the lower part of the stems of larger trees (Fig. 6).

The sapwood width varies within eucalypt species, i.e. 0.6 cm in *E. marginata* to 5.0 cm in *E. maculata* (Bamber 1985). In 9.5-year-old *E. grandis*, values between 0.9 and 4.8 cm were reported (Wilkins 1991).

By affecting tree growth, spacing will impact significantly on the heartwood content, e.g. the smaller trees grown at lower spacing will contain a lower proportion of heartwood. On a stand volume basis, the spacing 2 × 1 would yield 78% more total wood volume and 119% more sapwood than the spacing 3 × 3.

When the timber is directed to pulp production, as is the case with *E. globulus*, it should be taken into account that silvicultural practices that favor tree dimensions, i.e. wide plantation spacings, will also increase the proportion of heartwood and decrease the technological quality of the raw-material.

CONCLUSIONS

E. globulus heartwood starts in early ages and at the time of harvest for pulping represents a substantial part of the tree volume. Heartwood content is correlated with tree size, and large trees have more heartwood. Spacing influences the heartwood and sapwood volume production, and a higher proportion of heartwood is found with wider spacing. However, it is not the spacing per se that influences the tree heartwood and sapwood dimension but rather the tree dimensions. For pulping, smaller trees grown at a smaller spacing will have a better raw material quality in relation to heartwood content.

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