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# Variation of heartwood and sapwood in 18-year-old *Eucalyptus globulus* trees grown with different spacings

**Isabel Miranda · Jorge Gominho · Helena Pereira**

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**Abstract** Heartwood and sapwood development was studied in 18-year-old *Eucalyptus globulus* trees from pulpwood plantations with different spacings (3 × 2, 3 × 3, 4 × 3, 4 × 4 and 4 × 5 m), on cross-sectional discs taken at breast height. The trees possessed a large proportion of heartwood, on average 60% of the wood cross-sectional surface. Spacing was a statistically significant source of variation of heartwood area, which ranged between 99 and 206 $cm^2$ for the closer (3 × 2) and wider (4 × 5) spacings, respectively. There was a positive and high statistical significant correlation between heartwood diameter and tree diameter (heartwood diameter $= -0.272 + 0.616$ dbh; $r^2 = 0.77$; $P < 0.001$), and larger trees contained more heartwood regardless of spacing. Heartwood proportion in cross-section remained practically constant between spacings but increased with tree diameter class: 55.1, 62.2, 65.0 and 69.5% for diameter at breast height classes <15, 15–20, 20–25 and >25 cm, respectively. The sapwood width did not depend on tree diameter growth and remained practically constant at an average of 18 mm (range 15–21 mm), but sapwood area showed a good linear regression with tree diameter. Therefore, tree growth enhancement factors, such as wide spacings, will induce formation of larger heartwoods that can negatively impact raw-material quality for pulping. The increase in heartwood in relation with tree dimensions should therefore be taken into account when designing forest management guidelines.

**Keywords** *Eucalyptus globulus* · Heartwood · Sapwood · Plant density · Spacing

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I. Miranda · J. Gominho · H. Pereira (✉)
Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade Técnica de Lisoa, Tapada da Ajuda, 1349-017 Lisbon, Portugal
e-mail: hpereira@isa.utl.pt

J. Gominho
e-mail: jgominho@isa.utl.pt

## Introduction

Pulpwood plantations are valued by quantitative aspects related to stemwood volume on a unit area basis as well as by quality factors related to pulping and pulp characteristics. Optimising the forest-product chain by adoption of appropriate management practices and a product-oriented raw-material supply that takes into account quality-related wood variables is nowadays a key element in increasing the competitiveness of the forest sector.

In addition to more conventional stemwood characteristics, i.e. density, chemical composition and fibre biometry, heartwood content has recently been proposed as a quality variable for pulping due to its negative technological impact (Gominho and Pereira 2000, 2005; Gominho et al. 2001; Miranda et al. 2006, 2007; Morais and Pereira 2004; Quilhó et al. 2006). The accumulation of extractives in heartwood increases consumption of pulping chemicals, reduces pulp yields and decreases pulp brightness.

The proportion of sapwood and heartwood in a tree varies genetically with genera, species and families, and with factors such as silviculture, growing conditions, site and tree age (see reviews by Hillis 1987; Higgins 1984; Wilkins 1991). In *Eucalyptus globulus*, heartwood formation starts at an early age (3–5 years) and at harvest for pulping it represents a substantial part of the tree stem, attaining 60–75% of total tree height and 30–40% of total volume (Gominho and Pereira 2000; Gominho et al. 2001). Heartwood development is linked to tree size, and even-aged trees that grow more in diameter and height have more heartwood and a higher heartwood proportion in the stem (Gominho and Pereira 2000, 2005; Gominho et al. 2001; Miranda et al. 2006; Morais and Pereira 2004).

The usual practice in eucalypt plantation forestry, in Portugal and elsewhere, is to establish the plants at a 3 × 3 spacing (1,111 trees ha$^{-1}$), but numbers commonly range between 1,000 and 1,250 trees ha$^{-1}$. Though spacing strongly influences tree dimensions and stand volume production (West 2006), very few spacing trials exist for *E. globulus* and information regarding the influence of stand density on wood quality is limited (Miranda et al. 2003; Tomé et al. 1995; Delgado and Tomé 1997). The effect of spacing on heartwood development in 9-year-old *E. globulus* trees was examined by Gominho and Pereira (2005), who concluded that spacing influenced heartwood content because of its impact on tree dimensions, i.e. trees grown at higher plant densities had less heartwood. No studies are available for older trees which could give a more general insight into the influence of spacing in the supply to the pulping industry, since eucalypt rotations usually range from 9 to 15 years, occasionally extending to 18 years.

The objective of the present study was to increase the available knowledge on the influence of spacing on heartwood development by expanding the range of tree planting densities and age, in order to have a more robust assessment of the impact of these silvicultural practices. The study, therefore, evaluated the effect of varying planting densities between 500 and 1,667 trees ha$^{-1}$ in heartwood and sapwood development in *E. globulus* trees at a harvest age of 18 years.

## Materials and methods

The material was obtained from the spacing trial established by a pulp company (CELBI, Altri) with commercially available seeds of *E. globulus* Labill. at the site of Alto do Vilão, Furadouro (Portugal). The site is located in the central coastal region, approximately 10 km from the Atlantic (39°20′ N; 9°15′ W, 50 m altitude). The climate is of the Mediterranean type tempered by oceanic influence, with an annual rainfall of 607 mm and mean temperature of 15.2°C, and the soils are eutric cambisols developed on sandstones. The Alto do Vilão trial consists of two blocks, each with five plots with different tree spacings: 3 × 2 (1,667 trees ha$^{-1}$), 3 × 3 (1,111 trees ha$^{-1}$), 4 × 3 (833 trees ha$^{-1}$), 4 × 4 (625 trees ha$^{-1}$), and 5 × 4 (500 trees ha$^{-1}$). The trial was measured regularly and the results have been described in detail (Tomé et al. 1995; Soares and Tomé 1996; Soares et al. 2004). The trial was harvested at 18 years of age.

A total of 15 trees were sampled per plot per block, as follows: trees in each plot were sorted by diameter at breast height and divided into 15 classes of equal frequency. From each class, one tree, free of defects or other problems, with a diameter at breast height close to the quadratic mean diameter at breast height for the class, was selected for destructive sampling. Mean tree height and diameter of the sampled *E. globulus* trees and mean stand basal area and volume at the different planting densities are presented in Table 1.

A wood disc was taken at breast height from each sampled tree. On each disc, the delimitation of heartwood was determined by colour difference after water impregnation (the heartwood in *E. globulus* has a distinctive brown colour, which is visually distinguishable from the lighter sapwood) with an image analysis system. The disc area and heartwood were measured and the following variables were calculated: heartwood diameter and area, sapwood radial width and area, heartwood area proportion of the total disc area.

Production at stand level of total stemwood, heartwood and sapwood volumes was estimated for the different spacings assuming no mortality during the rotation, using the individual tree model of Tomé et al. (2007) based on tree diameter and total height, tree and heartwood diameters at breast height measured in this study and heartwood height calculated from total tree height using the model given by Morais and Pereira (2007).

**Table 1** Stand characteristics (basal area and volume over bark) (Soares et al., 2004), total tree height and diameter at breast height (dbh) of 18-year-old *Eucalyptus globulus* trees sampled from five different spacings

| Spacing (m × m) | Volume over bark (m$^3$ ha$^{-1}$) | Basal area (m$^2$ ha$^{-1}$) | Tree height (m) | dbh over bark (cm) |
|---|---|---|---|---|
| 3 × 2 | 378.9 | 34.88 | 22.9 (6.2) | 16.9 (5.8) |
| 3 × 3 | 341.6 | 31.11 | 23.8 (5.0) | 19.7 (5.6) |
| 4 × 3 | 321.7 | 28.85 | 25.3 (3.8) | 22.0 (5.3) |
| 4 × 4 | 284.6 | 25.84 | 24.6 (4.2) | 22.3 (6.2) |
| 4 × 5 | 292.2 | 26.03 | 25.3 (3.6) | 25.8 (5.5) |

Mean of 30 trees per spacing (15 trees per block), with the standard deviation in parentheses

The data were evaluated using analysis of variance at a 95% probability level. A simple regression model (response variable = $\beta 0 + \beta 1$ independent variable + $\varepsilon$) was applied to study the correlations between heartwood and sapwood dimensions and heartwood content with stem diameter at breast height.

## Results

### Tree dimensions and stand volume

Spacing had noticeable effects on tree diameter growth and trees responded to wider spacing and lower competition with greater individual dimensions (Table 1). Spacing was a statistically significant source of variation of diameter at breast height ($P < 0.001$) and height ($P = 0.030$).

The mean stand basal area and volume increased significantly with increase in tree density (Table 1). After 18 years of growth, trees planted at higher densities (1,667 trees ha$^{-1}$) had a basal area of 31.1 m$^2$ ha$^{-1}$ compared to 26.0 m$^2$ ha$^{-1}$ for trees planted at lower density (500 trees ha$^{-1}$). This increase was proportional to the number of trees in each spacing, since the increase in diameter of the individual trees due to wider spacing was not sufficient to offset the effect of lower stocking levels per hectare.

### Heartwood area and proportion

The mean heartwood cross-sectional area at breast height for the *E. globulus* trees ranged from 98.6 to 206.3 cm$^2$ (heartwood diameters of 103–156 mm), respectively, for the closer spacing (1,666 trees ha$^{-1}$) and wider spacing (500 trees ha$^{-1}$) (Table 2). The graphical representation of heartwood diameter as a function of tree diameter at breast height (Fig. 1) for all spacings shows a positive and significant correlation (heartwood diameter = −0.272 + 0.616 dbh; $r^2 = 0.77$; $P < 0.001$). Spacing was a statistically significant source of variation of heartwood area

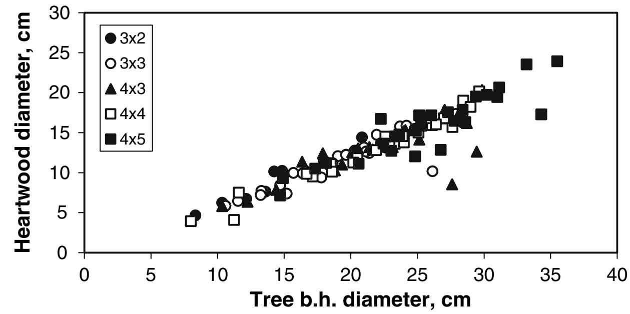


**Fig. 1** Heartwood diameter versus tree breast height diameter of 18-year-old *Eucalyptus globulus* planted with five spacings

($P < 0.001$), but differences were statistically significant only between the wider (4 × 5) and closer (3 × 2 and 3 × 3) spacings.

The proportion of heartwood in the cross-section at breast height was on average 59.9%, and remained practically constant between spacings without statistically significant differences ($P = 0.561$). Heartwood proportion increased with tree diameter class: 55.1, 62.2, 65.0 and 69.5% for diameter at breast height classes <15, 15–20, 20–25 and >25 cm, respectively.

### Sapwood thickness and area

Sapwood thickness at breast height was in the range of 14.9–20.7 mm, respectively, for the 3 × 3 and 4 × 5 spacings (Table 2) with a tendency to increase with increasing spacing. The difference between spacings was statistically significant ($P = 0.006$) but only between the closer (3 × 2) and the two wider spacings (4 × 4 and 4 × 5).

The mean sapwood area varied from 55.2 to 117.2 cm$^2$, respectively, for the 3 × 2 and 4 × 5 spacings (Table 2). Figure 2 represents sapwood area as a function of tree diameter at breast height for all spacings showing a positive trend (Sapwood area = −26.454 + 5.275 dbh; $r^2 = 0.63$; $P < 0.001$).

**Table 2** Heartwood, sapwood and total cross-sectional area, heartwood percentage in total cross-sectional area and sapwood width at 1.30 m of 18-year-old *Eucalyptus globulus* trees sampled from two blocks with different spacings

| Spacing (m × m) | Area (cm$^2$) | | Heartwood diameter (mm) | Sapwood width (mm) | Heartwood (% total area) |
|---|---|---|---|---|---|
| | Heartwood | Sapwood | | | |
| 3 × 2 | 98.6 (63.7) | 55.2 (27.0) | 103.1 (44.9) | 14.9 (4.9) | 58.4 (17.5) |
| 3 × 3 | 119.6 (70.1) | 73.8 (31.5) | 116.3 (42.1) | 17.5 (4.2) | 57.7 (13.9) |
| 4 × 3 | 146.9 (69.8) | 86.5 (35.0) | 132.4 (34.4) | 17.8 (4.6) | 61.8 (8.0) |
| 4 × 4 | 151.7 (80.1) | 91.2 (34.9) | 132.8 (41.8) | 18.9 (3.8) | 59.4 (9.9) |
| 4 × 5 | 206.3 (102.3) | 117.2 (48.3) | 156.8 (42.1) | 20.7 (6.6) | 62.0 (9.9) |

Mean of 30 trees per spacing with standard deviation in parentheses

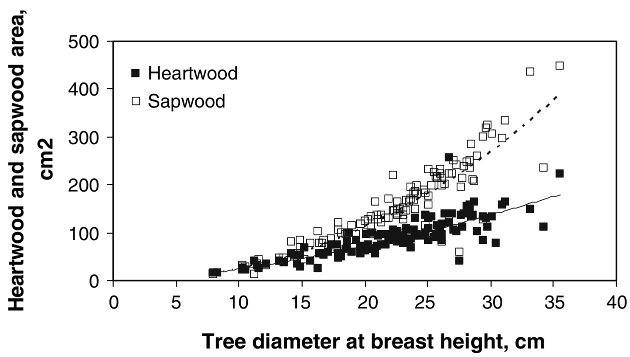


**Fig. 2** Heartwood and sapwood area versus tree breast height diameter of 18-year-old *Eucalyptus globulus* planted with five spacings

Influence of tree diameter on heartwood and sapwood

The influence of tree diameter on heartwood and sapwood dimensions at breast height was assessed by a correlation analysis between tree, heartwood and sapwood dimensional variables and is shown graphically in Figs. 1, 2, 3.

Heartwood area and diameter were strongly correlated with tree diameter ($r^2 = 0.857$; $P < 0.000$) as well as sapwood area ($r^2 = 0.825$; $P < 0.000$), while sapwood width showed a lower, although highly significant, correlation ($r^2 = 0.447$; $P < 0.000$). The correlation of heartwood proportion with tree diameter was significant although small ($r^2 = 0.204$; $P = 0.024$) and very highly significant with heartwood diameter ($r^2 = 0.330$; $P < 0.000$).

## Discussion

Initial spacing in plantation forestry is known to influence competition for light, moisture and nutrients and thereby tree growth in diameter and height (West 2006), while basal area and volume production per unit area will result from the combined effect of the number of trees and their dimensions. In the studied *E. globulus* spacing trial higher values of basal area and stand volume were associated with closer spacings and higher values of mean diameter at breast height were associated with wider spacings, as shown in Table 1 (Tomé et al. 1995; Soares and Tomé 1996; Soares et al. 2004).

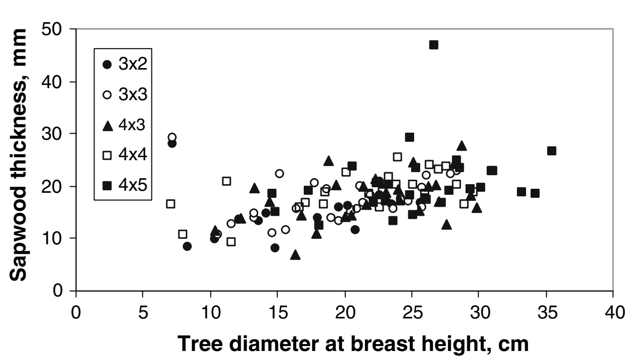


**Fig. 3** Sapwood thickness versus tree breast height diameter of 18-year-old *Eucalyptus globulus* planted with five spacings

The 18-year-old *E. globulus* trees possessed a large proportion of heartwood at breast height: on average 60% of the wood cross-sectional surface was transformed into heartwood, with values ranging between 58 and 62% for 3 × 2 and 4 × 5 spacings, respectively (Table 2). Recently, Miranda et al. (2006) also reported high values of heartwood proportion at breast height, between 68 and 78% for 18-year-old *E. globulus* trees, and data are also available for younger *E. globulus* trees: 52–54% in 12-year-old (Morais and Pereira 2004), 43% in 9-year-old (Gominho and Pereira 2000), and 29–61% in 8-year-old trees (Miranda et al. (2007). However, these studies indicated that it is not age but tree dimensions, particularly tree diameters that are the main factors responsible for heartwood development. This is in agreement with similar results obtained for other eucalypts, i.e. *Eucalyptus grandis* (Wilkins 1991) and for other species, i.e. *Tectona grandis* (Bhat 1995), *Pinus contorta* (Yang and Murchison 1992), *Juglans nigra* (Woeste 2002), *Acacia melanoxylon* (Knapic and Pereira 2005) and *Pinus canariensis* (Climent et al. 2002), although a few authors report the inverse correlation in *Pinus silvestris*, *Picae abies* and *Cryptomeria japonica* (Karkkainen 1972; Hillis 1987).

Therefore, it is to be expected that heartwood diameter is positively related with tree diameter. This was already shown in 9-year-old *E. globulus* trees grown at various close spacings (2 × 1 to 3 × 3) by Gominho and Pereira (2005), who concluded that heartwood development was influenced by tree growth and not by the silvicultural treatment as such.

In the present study, the trees were older and a larger range of spacings was tested, thereby allowing a stronger effect of differing competition on tree growth. On average trees in the 4 × 5 spacing were twice as large as in the 3 × 2 spacing (Table 2), although tree dimensions also varied to a large extent within each spacing (i.e. the coefficients of variation of the mean stemwood area were about 47%, Table 2). Heartwood development varied with tree dimensions and not with spacing as such, as shown in Fig. 1, and a good predictive model of heartwood dimensions based on tree diameter could be obtained. Based on this model, it can be estimated that heartwood starts to form when tree diameter is about 3 cm and increases thereafter linearly by a ratio of 0.6. Therefore, the proportion of heartwood in the breast height cross-section remains independent of spacing per se (Table 2).

**Table 3** Theoretical stand production estimates of total stemwood, heartwood and sapwood volumes for 18-year-old *Eucalyptus globulus* trees with five different spacings (considering no mortality during the rotation), using the individual tree model of Tomé et al. (2007), the diameter at breast height of tree and heartwood measured in this study and the heartwood height calculated from total tree height using the model given by Morais and Pereira (2007)

| Spacing (m × m) | Stand density (trees $ha^{-1}$) | Stemwood volume ($m^3$ $ha^{-1}$) | Heartwood volume ($m^3$ $ha^{-1}$) | Sapwood volume ($m^3$ $ha^{-1}$) | Heartwood volume (% of total volume) |
|---|---|---|---|---|---|
| 3 × 2 | 1,666 | 586.5 | 196.4 | 390.0 | 33.5 |
| 3 × 3 | 1,111 | 435.4 | 149.1 | 286.3 | 34.2 |
| 4 × 3 | 833 | 389.3 | 132.8 | 256.5 | 34.1 |
| 4 × 4 | 625 | 295.0 | 100.7 | 194.2 | 34.1 |
| 4 × 5 | 500 | 299.4 | 109.1 | 190.3 | 36.4 |

The sapwood width at breast height of these 18-year-old *E. globulus* trees varied from 1.5 to 2.1 cm (Table 2) and is in the range of values (1.6–1.9 cm) reported for *E. globulus* at the same age by Miranda et al. (2006) and similar to the values between 1.6 and 3.7 cm reported for 8- and 9-year-old trees (Gominho and Pereira 2005; Miranda et al. 2007). Sapwood width varied little with tree diameter at breast height (Fig. 3), but sapwood area varied exponentially (Fig. 2). A positive variation of sapwood area with tree radial growth has been shown for *E. globulus* trees in various conditions, i.e. at different plant densities (Gominho and Pereira 2005), in trees grown at different sites (Miranda et al. 2007), and in fertilised and irrigated trees (Miranda et al. 2006). The same was also reported for other species, i.e. *Picea abies* (Sellin 1996), *Pseudotsuga menziesii*, *Abies porcera* and *Pinus ponderosa* (Grier and Waring 1974), *Pinus banksiana* and *Larix laricina* (Yang et al. 1985), *Abies balsamea* (Margolis et al. 1988), *Pinus pinaster* (Pinto et al. 2004, 2005; Knapic and Pereira 2005).

Sapwood is related to crown dimensions and leaf area in accordance to the pipe model theory of conductive area in plants (Shinozaki et al. 1964). Therefore, wider spacings that allow a larger crown development will translate into larger sapwoods, as shown in Table 2, even if the width of the conductive circular sapwood remains fairly constant at about 2 cm. For instance, a comparison between 4 × 5 and 3 × 2 spacings shows a mean sapwood area of 117 and 55 $cm^2$, while sapwood width varied only between 2.1 and 1.5 cm, respectively (Table 2). This indicates that sapwood radial width in one species may be independent of tree age and dimensions, as has also been shown in other species, particularly conifers (Pinto et al. 2004; Sellin 1994, 1996; Yang and Murchison 1992), and that heartwood is formed to regulate the width of sapwood to this species' mean value, despite small variations in relation to crown size and transpiration.

In practical terms, the results confirm that heartwood formation depends on diameter growth: larger trees will have larger heartwoods that correspond to a higher proportion of the tree diameter. Therefore, tree growth enhancement factors, including wide spacings, will induce formation of larger heartwoods. Stems with large diameters as given by long rotations and wide spacings will contain more heartwood and consequently have lower pulpwood quality. The increase in heartwood in relation with tree dimensions should, therefore, be taken into account when establishing forest management guidelines.

The impact of different spacings in eucalypts on an 18-year rotation may be calculated using estimates of tree volume and heartwood volume production. Although the vertical development of heartwood within the tree was not studied here, it was sufficiently reported in previous studies as closely following the tree profile (Gominho and Pereira 2005; Morais and Pereira 2007). A tree volume equation developed by Tomé et al. (2007) with data that represent the entire area of eucalypt plantations in Portugal was used and applied to estimate total stemwood volume and heartwood volume using as input variables, respectively, tree diameter at breast height and tree height, and heartwood diameter at breast height and heartwood height were estimated according to Morais and Pereira (2007). The estimates obtained are reported in Table 3 for different theoretical stand densities corresponding to the initial planting density, i.e. without tree mortality. Heartwood represents 33.5% of the total stemwood volume production in the 3 × 2 spacing and 36.4% in the 4 × 5 spacing, showing that spacing has an impact on the heartwood-to-sapwood ratio of stemwood production. Although the difference between the various spacings in the range studied here was not very pronounced, better stemwood quality for pulping is achieved in the closer spacings as regards a lower proportion of heartwood.

## Conclusions

*Eucalyptus globulus* trees at 18 years of age possess a considerable proportion of heartwood at breast height that is very highly and positively correlated with stem diameter. By contrast, sapwood width is relatively independent of tree dimensions. This means that more heartwood is found in larger trees and that forest practices aiming at increasing individual tree radial growth also increase heartwood. Spacing impacts tree dimensions and therefore heartwood quantity. Trees grown with lower plant densities will have more heartwood than those grown with higher plant densities and the balance of sapwood and heartwood production on a unit area basis should be considered when planning initial spacing.

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