Juvenile Wood Characterization of *Eucalyptus botryoides* and *E. maculata* by using SilviScan

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The wood properties of 6-year-old *Eucalyptus botryoides* and *Eucalyptus maculata* point towards a possible aptitude for solid-wood end uses. Samples from *E. botryoides* and *E. maculata* were characterized regarding within-tree variation in wood density, radial and tangential fibre width, fibre wall thickness, fibre coarseness, microfibril angle, and stiffness based on SilviScan measurements taken radially from the pith outwards at varying stem height levels. The mean values of the studied wood properties for *E. botryoides* and *E. maculata* were, respectively: density 507 kg m^{-3} and 695 kg m^{-3}, radial fibre width 17.4 µm and 17.2 µm, tangential fibre width 16.7 µm and 16.9 µm, fibre wall thickness 1.8 µm and 2.5 µm, fibre coarseness 161.2 μgm^{-1} and 212.9 μgm^{-1}, microfibril angle 15.5° and 14.7°, and stiffness 9.6 GPa and 12.1 GPa. The variation in wood stiffness was explained to a large extent by microfibril angle and wood density variations. The results of the scans, along with the wood variability, indicated that both species should be considered for solid wood products or pulp production.

Keywords: Wood density; Microfibril angle; Wood stiffness; SilviScan; Eucalyptus botryoides; Eucalyptus maculata

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INTRODUCTION

The *Eucalyptus* genus originated in Australia and Tasmania (Boland *et al.* 1992), but several species are now widely planted elsewhere, totalling 18 million ha in 90 countries. These species are planted in tropical and subtropical regions of Africa, South America, Asia, and Australia, as well as in temperate regions of Europe, South America, North America, and Australia (Rockwood *et al.* 2008).

Eucalypt wood is known worldwide as a common raw material for pulping, and most of the plantations are directed for the paper industry. Intensive research has concentrated on the pulp fibre quality of different commercial eucalypt species, *e.g. E. globulus* and hybrids such as *E. urograndis*, although species diversification has also been proposed (Pirralho *et al.* 2014; Neiva *et al.* 2015). The use of eucalypts for their solid wood value is promising and an object of increasing interest (Nolan *et al.* 2005). Nevertheless, such use requires targeted wood characterization for breeding towards specific goals, *e.g.* for construction purposes. The availability of eucalypt trees that are over-sized for pulping, the shortage of timber-oriented species, and the advantage of increasing production diversity in eucalypt forests call for consideration of this potential use. The benefits regarding the promotion of biodiversity and increased forest sustainability add to the economic advantages.

A recent study on the wood density of various eucalypt species showed that *E. botryoides* and *E. maculata* have suitable density and promising growth values, suggesting their potential quality as timber sources (Knapic *et al.* 2014). For this purpose, wood anatomical characteristics are also important, because performance and product value depend on a wide range of interlinked fundamental wood characteristics (Huang *et al.* 2003). There is extensive wood anatomical data for *E. globulus*, including variation with site, age, and genetics, as compiled by Pereira *et al.* (2011). For other eucalypt species, the information is less thorough, *e.g.*, *E. grandis*, *E. tereticornis*, *E. saligna*, and *E. camaldulensis* (Pereira *et al.* 2011). The information is also scarce for several hybrids (Prinsen *et al.* 2012) and many other species, including *E. maculata* and *E. botryoides*.

The most important properties for structural uses are density, microfibrillar angle (MFA), and modulus of elasticity (MOE). The density is strongly correlated with the structural strength of wood, and the MFA has a strong influence on the stiffness, strength, and dimensional stability of the wood. Booker *et al.* (1998) found correlations between the MOE, MFA, and density. Lachenbruch *et al.* (2010) studied density and MFA as the most suitable parameters to predict MOE in Douglas-firs. The importance of MFA on wood quality is well established for softwoods (Hori *et al.* 2002), but is less clear for hardwoods (Donaldson 2008).

The MOE of wood decreases as the MFA increases (Cave 1968; Cave and Walker 1994; Walker and Butterfield 1995; Barnett and Bonham 2004). In *Eucalyptus* wood, the relationship between the MFA and mechanical traits has been investigated. The results indicated that MFA is the prime determinant of MOE (Evans and Ilic 2001; Yang and Evans 2003), as well as a useful parameter to indicate MOE and strength in juvenile eucalypts from short-rotation plantations (Hein and Lima 2012). Studies on MFA prediction have found correlations with lignin content (Baillères *et al.* 1995; Barnett and Bonham 2004; Via *et al.* 2009; Hein *et al.* 2010). The microfibril angle has also been known to influence dimensional changes in wood with changes in the moisture content (Meylan 1968; Yamamoto *et al.* 2001). Most shrinkage takes place transversely when MFA is small, but as it increases, the longitudinal component of shrinkage increases (Hein and Lima 2012). Stiffness, measured by the MOE, is an important measure of the suitability of structural timber for construction, as it indicates the extent to which a board will bend under load (Nolan *et al.* 2005; Evans 2006).

Trees from *E. botryoides* and *E. maculata* were studied for important timber properties using the SilviScan instrument at Innventia (Stockholm, Sweden). This tool is a system of connected instruments developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Melbourne (Australia) that was designed for the rapid analysis of radial variations in growth, wood, and fibre properties of wood samples, including increment cores (Evans 1994, 2014), making it a more efficient method when compared with the individual technologies. The SilviScan integrates three measurement principles: image analysis of fibre cross-sections, X-ray absorption, and diffraction of the wood. The measurements can be performed along radii from the pith to the bark, allowing for characterization of the radial variations of a large number of important properties of the wood and fibres. Wood density (WD), along with fibre width in the radial (FWR) and tangential (FWT) directions, is measured. Fibre coarseness (FC) is calculated from FWR, FWT, and WD, and fibre wall thickness (FWT) is calculated from WD, FWR, FWT, and the fibre wall density. The MFA is estimated from interpretation of the X-ray diffractograms, and the MOE is estimated from WD and diffractogram data.

The objective of this study is to evaluate the vertical and horizontal variation on young wood of *E. botryoides* and *E. maculata* characteristics (density, MFA, wood stiffness, fiber, and vessel). Overall, the study aims at characterizing the wood quality of young *E. botryoides* and *E. maculata* trees using SilviScan measurements, setting the grounds for a larger and broader study of these species. For this purpose, wood density, fibre biometry, MFA, and MOE were analysed, including their radial and axial variation within the stem.

EXPERIMENTAL

For this study, 6-year-old trees of *E. botryoides* and *E. maculata* were taken from an experimental site located in the campus fields of the School of Agriculture (ISA), University of Lisbon, at Tapada da Ajuda, Lisboa, Portugal (38° 42´ N; 09° 10´ W). A total of four trees were studied, two of each species. The study of such young trees allows consideration for either pulp or solid wood uses. The trees were planted from seeds originating from Australia, in February 2007, in rows of 3 m × 3 m spacing, and without fertilization.

The region in which the trees were planted is under the influence of a mesothermal, humid climate, with a dry season in the summer extending from June to August, with temperatures > 10 °C in the coldest month and ≤ 22 °C in the hottest month. The soil is a vertisol characterized by a fine, or medium to fine, texture, derived from tuffs or basalts, frequently with limestone on the inferior horizons, or from calcareous rock (in much less extension).

Before felling, the lower portion of the north side of the stem was marked with ink to ensure that the wood properties were measured in the same direction for all of the trees, as well as the same height levels within the trees. After felling, the north line was marked throughout the stem and the height of the stump. The total tree height and the height to the lowest living branch were measured.

From each tree, four discs were cut at heights of 1.3 m, 25% and 60% of the total height, and close to the top height at a stem diameter of approximately 7 cm. The four discs samples at each height level were used for: SilviScan measurement, documentation, pulping, and an extra to be stored as a reserve or for future purposes. The discs were marked with a sample ID and north direction. They were debarked and packed in tightly sealed plastic bags. Digital images were obtained of the full cross-sections from the lower, unmarked sides of each disc intended for SilviScan analysis. A sample bar with a rectangular cross-section of approximately 16 mm × 16 mm was immediately cut along the diameter from the mark on the northern side *via* the pith to the southern side of the disc, with the pith close to the middle of the bar.

The fresh samples were kept submerged in 96% ethanol for 3 weeks (changing the solution once a week). This procedure was performed to avoid fibre collapse during drying, which would affect the structure and might make it impossible to analyse the fibres and vessels with SilviScan. After the water was exchanged for ethanol, the samples could dry without risk of fibre collapse. The samples were then allowed to dry in room temperature conditions, packed, and brought to Innventia.

At Innventia, the samples were prepared for measurement according to the standard procedure: the sample bar was glued upon a MDF board and cut with precision twin-blade saws to the final dimensions of 2-mm thickness (tangential direction of wood) and 7-mm height (longitudinal direction) from pith to bark.

The sample strips were then sanded on the top to promote good images of the fibre cross-section. The measurements were performed on samples in equilibrium with the conditioned atmosphere of the laboratory: 23 ºC and 43% relative humidity.

The length, width, and height of the sample strip were callipered. The sample was weighed, and its average density calculated for later use in the calibration. The sample strips were analysed with three different methods, scanned from pith to bark on the following measurement units: i) the optical cell scanner (CSIRO, Melbourne, Australia); ii) the X-ray density scanner; and iii) the X-ray.

Consecutive images of the polished top surface of the strip (transverse section) were taken with a video microscope, and the locations and sizes of vessels and fibres were determined. In this study, the properties of the wood and fibres were emphasised. The fibre widths in the radial and tangential directions were determined and presented as averages for 2-mm-wide consecutive intervals.

For softwoods, these averages are calculated for 25-µm intervals, but in this case, 2-mm intervals were preferred because of disturbances from larger size vessels. The annual rings were not visible. Figure 1 displays the radial images of *E. botryoides* and *E. maculata* at dbh (diameter at breast height, 1.30 m).

Fig. 1. Radial images of the cross-sections of *E. botryoides* (a) and *E. maculata* (b)

The strips were then measured with X-ray absorption with radial intervals of 25 µm. The information from the vessels, fibre widths, and wood density was combined to calculate the radial variation of fibre wall thickness.

Finally, the strips were measured with X-ray diffraction. A focused X-ray beam interacted with the wood structure, providing a radial sequence of diffraction patterns. From these diffractograms, the radial variation of the microfibril angle of the fibres was estimated and presented as averages for 2-mm wide intervals.

By combining data on wood density and information from the diffractograms, the wood stiffness was estimated (acoustic MOE).

A statistical analysis was performed using SPSS statistical software (version 19.0, SPSS Inc., Chicago, IL, USA). A statistical ANOVA analysis was performed for the variation with tree height (1.3 m, 25% and 60% tree height, and top-a diameter ≤ 6 cm) and radial position for wood density, radial and tangential fibre width, fibre wall thickness, fibre coarseness, microfibril angle, and wood stiffness.

RESULTS AND DISCUSSION

The average values and ANOVA results for wood density, radial and tangential fibre width, fibre wall thickness, fibre coarseness, microfibril angle, and wood stiffness are summarized in Table 1. The average values were calculated with the same weight for all of the individual data points.

Table 1. Average Values (and Standard Deviation) and ANOVA Results for the Seven Properties Studied for *E. botryoides* and *E. maculata*

		Wood Density (kg m^{-3})	Radial Fibre Diameter (µm)	Tangential Fibre Diameter (µm)	Fibre Wall Thickness (µm)	Fibre Coarse-ness (µg m^{-1})	Microfibril Angle (°)	Wood Stiffness (GPa)
E. botryoides		506.9 (± 73.37)	17.4 (± 0.96)	17.2 (± 0.77)	1.8 (± 0.29)	161.2 (± 24.49)	15.5 (± 5.30)	9.6 (± 3.20)
E. maculata		695 (± 78.42)	16.7 (± 0.71)	16.9 (± 0.88)	2.5 (± 0.38)	212.9 (± 36.47)	14.7 (± 4.87)	12.1 (± 3.14)
2-Way ANOVA								
Height Level	*E. botryoides*	*p = 0.008	NS	NS	*p = 0.01	*p = 0.01	*p = 0.000	*p = 0.003
	E. maculata	NS	NS	*p = 0.01	NS	NS	*p = 0.000	*p = 0.000
Radial Variation	*E. botryoides*	NS	NS	NS	NS	NS	*p = 0.005	*p = 0.023
	E. maculata	NS	*p = 0.030	*p = 0.012	NS	NS	*p = 0.038	NS

NS- Not significant; *- Difference significant at 0.05 level

Eucalyptus botryoides had an average wood density of 507 kg m^{-3}, which ranged from 401 kg m^{-3} to 674 kg m^{-3}, and an average stiffness of 9.6 GPa, ranging from 5.3 GPa to 16.2 GPa. *Eucalyptus maculata* had an average wood density of 695 kg m^{-3}, ranging from 438 kg m^{-3} to 843 kg m^{-3}, and an average stiffness of 12.1 GPa, ranging from 7.5 GPa to 18.2 GPa.

For *E. botryoides*, the variation in stiffness was statistically significant for both the tree height and radial variation ($p = 0.003$ and $p = 0.023$, respectively), while the variation in density variation was significant with height levels ($p = 0.008$), but not radially ($p > 0.05$). For *E. maculata*, the two-way ANOVA results showed that the variation in stiffness was highly significant with tree height ($p = 0.000$), but not with radial position ($p > 0.05$), while the variation in density was not significant with tree height or radial position ($p > 0.05$).

The density radial variation at the different height levels is shown in Fig. 2.

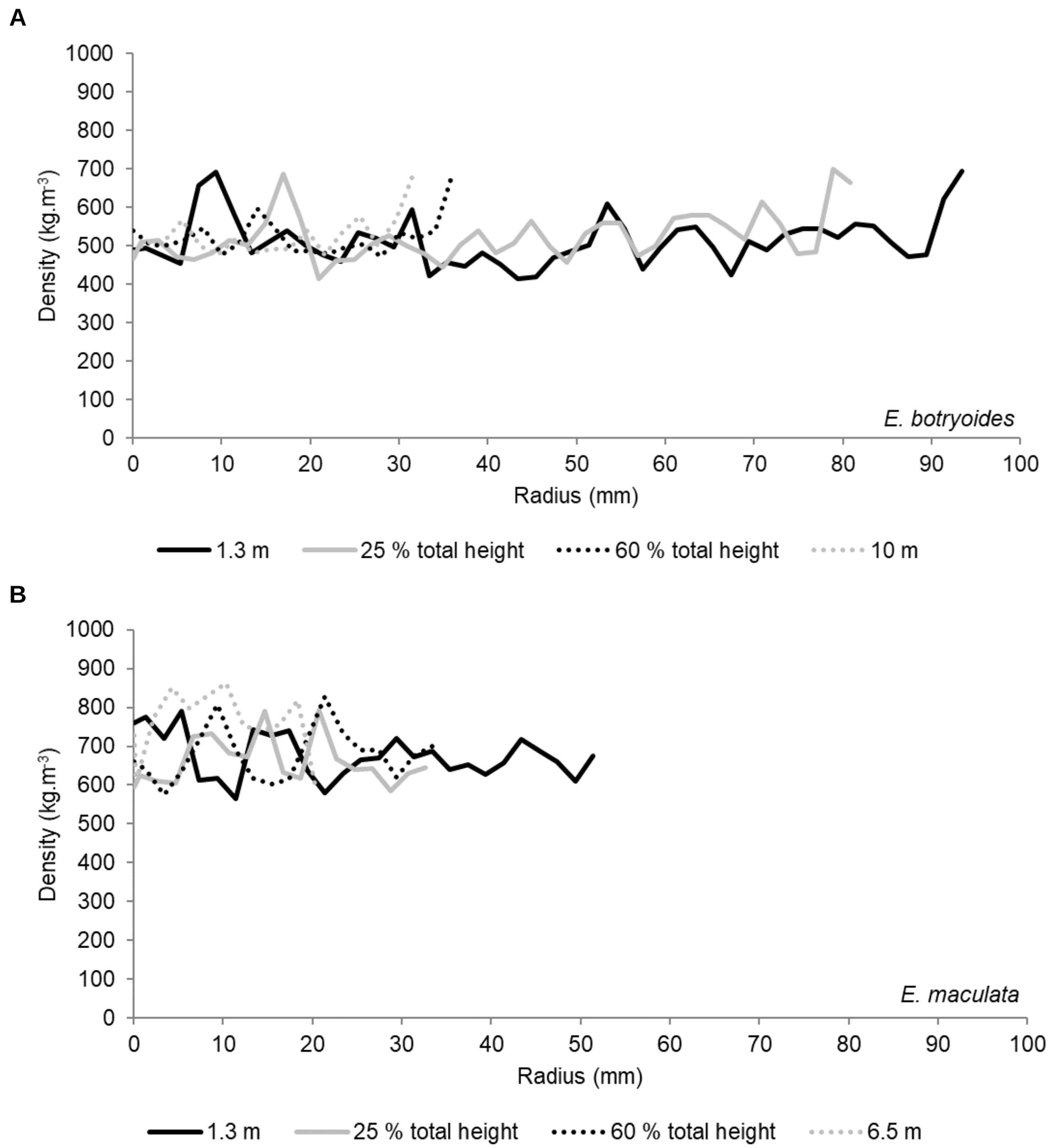

Fig. 2. Radial variation of density at various height levels (1.3 m, 25%, and 65% of tree height, and top) in *E. botryoides* (a) and *E. maculata* (b)

The variation in wood density was very similar for both species, although the mean values were rather different, at 695 kg m^{-3} and 507 kg m^{-3} for *E. botryoides* and *E. maculata*, respectively. These values are in accordance with average wood densities in the literature. Values of 620 kg m^{-3} and 550 kg m^{-3} were recorded for young *E. botryoides* and *E. maculata*, respectively (Knapic *et al*. 2014), and a value of 550 kg m^{-3} was recorded for 6.5-year-old *E. maculata* (Mackensen and Bauhus 2003). *E. globulus*, the most industrialized and studied *Eucalyptus* species, has presented a range of values between 380 kg m^{-3} and 920 kg m^{-3} for trees between 1 year of age and 30 years of age (Pereira *et al.* 2011). For young *E. globulus* trees, wood basic density values ranging from 410 kg m^{-3} to 480 kg m^{-3} have been reported for 1-year-old trees (Silva 1998), and values ranging from

460 kg m^{-3} to 570 kg m^{-3} have been reported for 5- to 7-year-old trees (Raymond and Muneri 2001). Wood density values vary between other eucalypt species, with values of 587 kg m^{-3} and 580 kg m^{-3} observed for 15- to 16-year-old trees of *E. fastigata* and *E. nitens,* respectively (Kibblewhite *et al.* 2004), and a value of 478 kg m^{-3} observed for 13-year-old *E. nitens* (Blackburn *et al.* 2010).

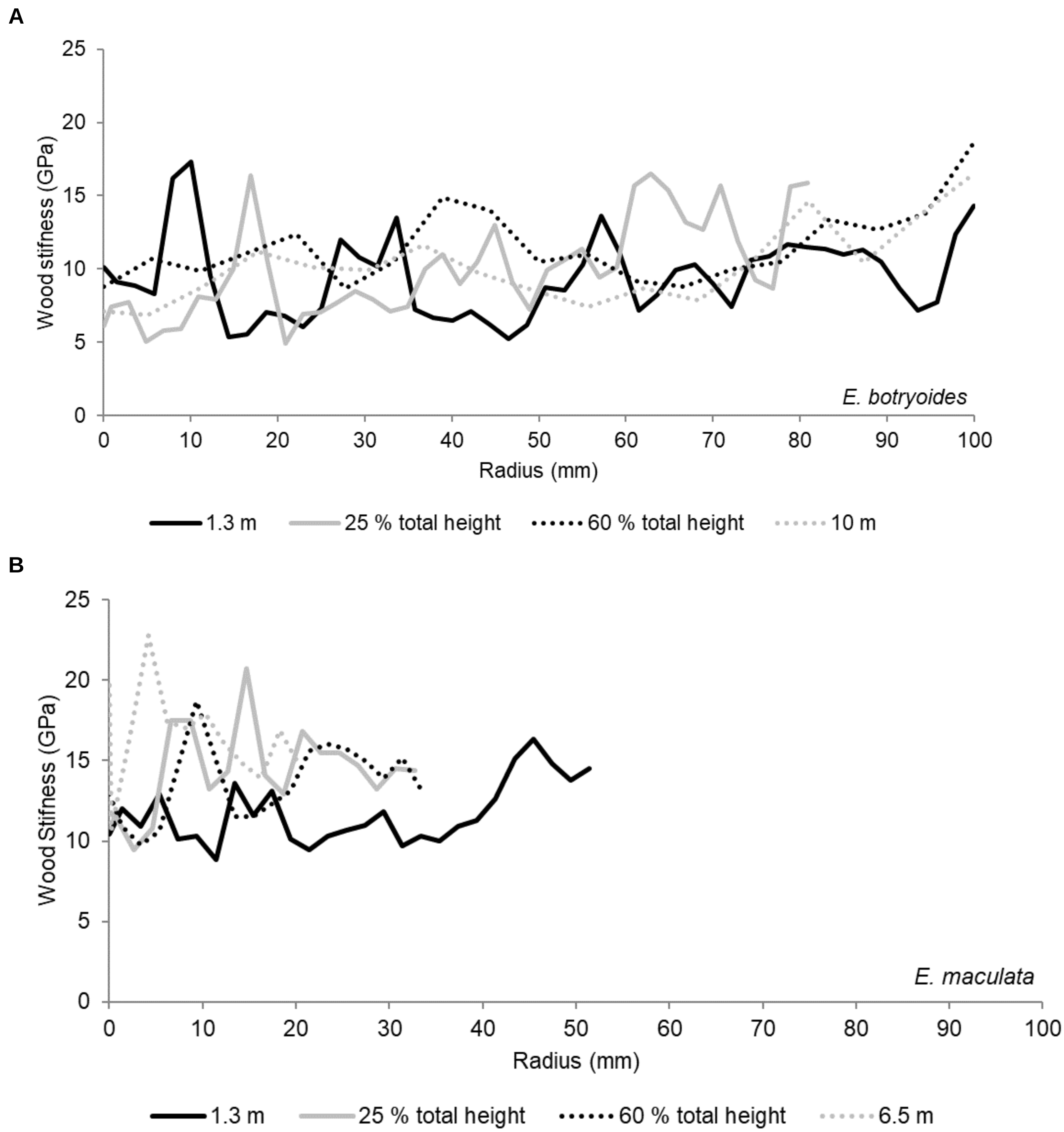

Fig. 3. Radial variation of wood stiffness at various height levels (1.3 m, 25%, and 65% of tree height, and top) in *E. botryoides* (a) and *E. maculata* (b)

Wood stiffness showed a higher variation along the radial direction, especially in the innermost half of the radius. Wood stiffness also changed with tree height level, with lower values at 1.3 m, and higher values at the top, as shown in Fig 3. Wood stiffness values were very similar between both species. These values are in the upper range of results reported for 78-month-old *E. grandis* trees, with values ranging from 4.5 GPa to 11 GPa (Hein *et al*. 2012).

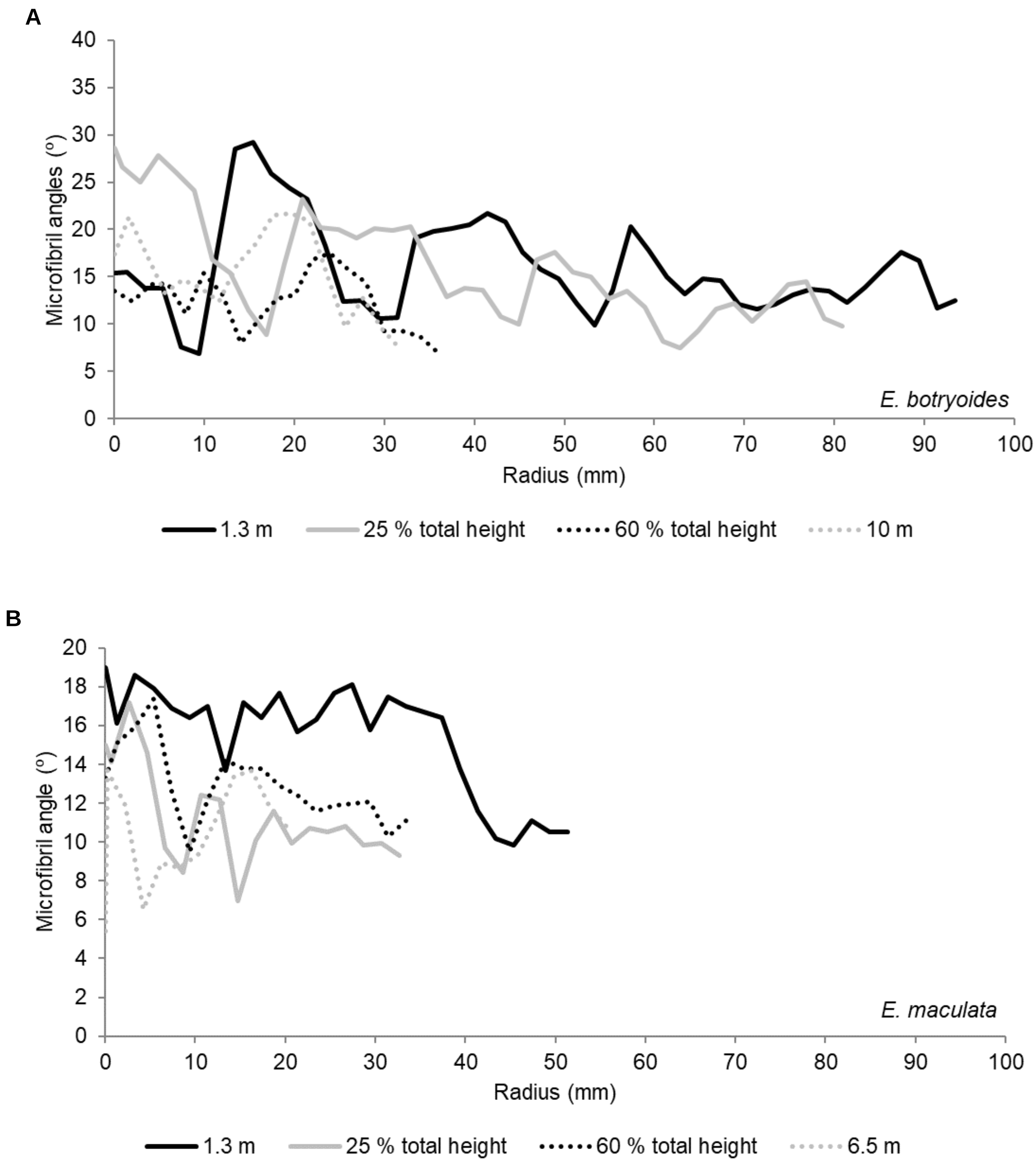

Fig. 4. Radial variation of microfibril angle at various height levels (1.3 m, 25%, and 65% of tree height, and top) in *E. botryoides* (a) and *E. maculata* (b)

Fibre width was very similar in the radial and tangential directions, with mean values of 17.4 µm and 17.2 µm in *E. botryoides*, and 16.7 µm and 16.9 µm in *E. maculata*, respectively. Fibre wall thickness was 1.8 µm and 2.5 µm for *E. botryoides* and *E. maculata*, respectively.

The values for radial fibre diameter, tangential fibre diameter, and thickness were very similar in both species. The fibre wall thickness presented similar values to those seen in *E. fastigata* (1.59 µm) and *E. nitens* (1.53 µm), also using SilviScan technology (Kibblewhite *et al.* 2004). Fibre coarseness values were higher than those seen in *E. fastigata* (114 µg m^{-1}) and *E. nitens* (106 µg m^{-1}), again using SilviScan technology (Kibblewhite *et al.* 2004).

On average, the microfibril angle was 15.5º and 14.7º, and fibre coarseness was 161.2 µg m^{-1} and 212.9 µg m^{-1}, for *E. botryoides* and *E. maculata*, respectively. Both species showed statistically significant microfibril variation for both tree height and radial variation ($p = 0.000$ and $p = 0.005$ for *E. botryoides*, and $p = 0.000$ and $p = 0.038$ for *E. maculata*). Figure 4 displays the radial variation of the microfibril angle at the various height levels. Microfibril angle showed a higher radial variation at lower heights, and in the last 50% of the radius, there seemed to be a more homogeneous pattern of variation with height.

The microfibril angle values were similar to those found for *E. fastigata* and *E. nitens* (15.1º and 13.5º, respectively) (Kibblewhite *et al.* 2004). Values ranging from 8º to 23º were found for 78-month-old *E. grandis* trees (Hein *et al.* 2012).

Microfibril angle has major effects on the stiffness and longitudinal shrinkage of wood, and it is of key importance to timber quality (Hein and Lima 2012). Figure 5 displays the correlation between MFA and MOE, with $R^2 = 0.85$ and $R^2 = 0.78$ for *E. botryoides* and *E. maculata*, respectively.

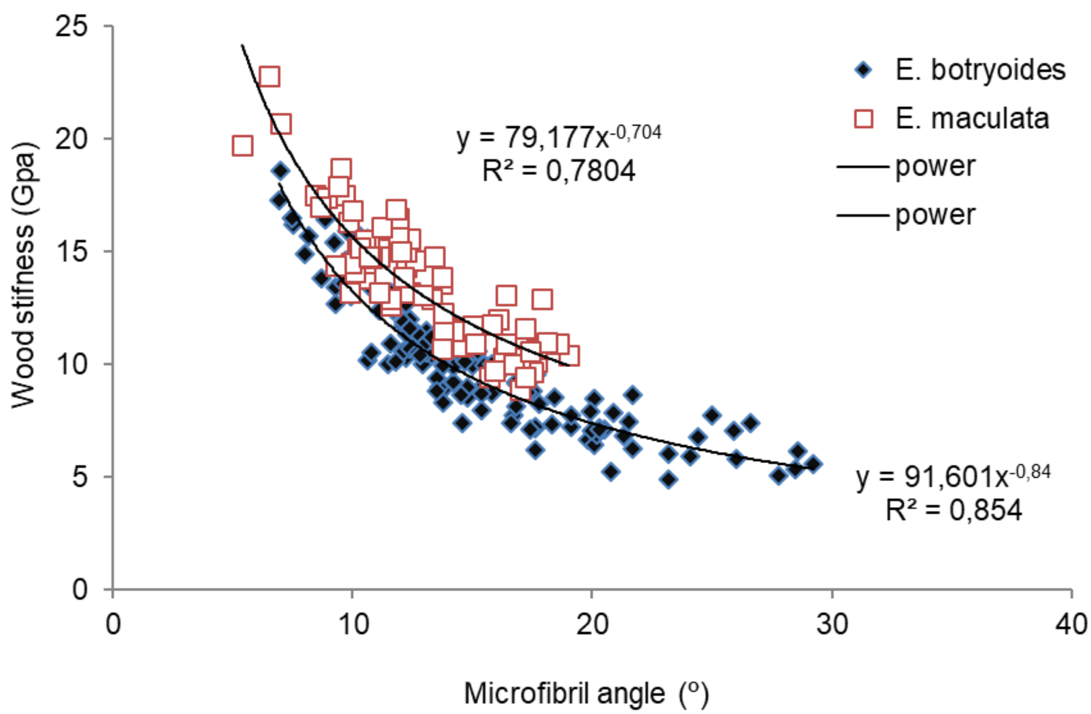

Fig. 5. Correlation between microfibril angle and wood stiffness for *E. botryoides* and *E. maculata*

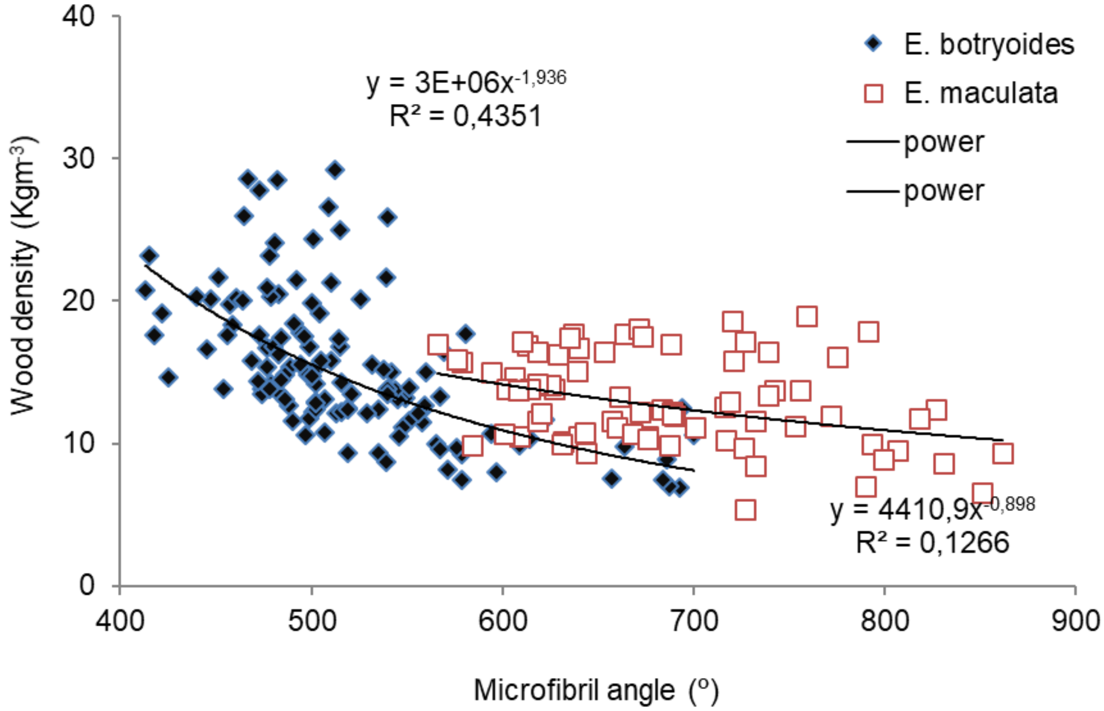

Fig. 6. Correlation between microfibril angle and wood density for *E. botryoides* and *E. maculata*

These values are in accordance with previous studies for *E. delegatensis* (Evans and Ilic 2001) and for *E. globulus*, *E. nitens*, and *E. regnans* (Yang and Evans 2003). Density was also positively correlated with MOE (Fig. 6), with R^2 = 0.71 and R^2 = 0.44 for *E. botryoides* and *E. maculata*, respectively. Evans and Ilic (2001) found a stronger correlation (R^2 = 0.92) between MOE and wood density.

The results of this study allowed for the characterization of the wood of both eucalypt species, for which little information previously existed. Both species differed in wood density (higher for *E. maculata*), but were similar regarding fibre characteristics, except for fibre cell wall thickness, which led to differences in coarseness (higher in *E. maculata*). Consequently, the wood stiffness was higher for *E. maculata*. In fact, the average wood density of *E. maculata* was 37% higher than that of *E. botryoides*, which can be understood from its 39% higher fibre wall thickness and 32% higher fibre coarseness, resulting in a higher wood stiffness (26%). Despite some within-tree variation of wood properties, the overall variations were of small magnitude, and the stems could be considered particularly homogeneous.

The data achieved, along with the wood variability, showed that both species may be considered within the context of the production of pulp or solid wood products.

CONCLUSIONS

1. Both eucalypt species differed in their mean properties.
2. Wood density, fibre wall thickness, and coarseness were influenced by the height level in *E. botryoides*, and radial fibre diameter was influenced by the height level in *E. maculata*. The tangential fibre diameter was influenced both by height level and radial variation in *E. maculata*.

3. The microfibril angle was influenced both by height level and radial variation for both *E. botryoides* and *E. maculata*.
4. Wood stiffness was influenced by height level in *E. botryoides* and *E. maculata*, and by radial position in *E. botryoides.*
5. Microfibrillar angle variation accounted for 85% and 78% of the variation in wood stiffness for *E. botryoides* and *E. maculata*, respectively.
6. Wood density variation accounted for 71% and 44% of the variation in wood stiffness in *E. botryoides* and *E. maculata*, respectively.
7. The values obtained for wood density and MOE point towards a prospective aptitude for solid-wood end uses or pulp production of *E. botryoides* and *E. maculata*.

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