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Heartwood and sapwood in eucalyptus trees: non-conventional approach to wood quality

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ABSTRACT

This study evaluated the quality of heartwood and sapwood from mature trees of three species of *Eucalyptus*, by means of the qualification of their proportion, determination of basic and apparent density using non-destructive attenuation of gamma radiation technique and calculation of the density uniformity index. Six trees of each species (*Eucalyptus grandis* - 18 years old, *Eucalyptus tereticornis* - 35 years old and *Corymbia citriodora* - 28 years old) were used in the experimental program. The heartwood and sapwood were delimited by macroscopic analysis and the calculation of areas and percentage of heartwood and sapwood were performed using digital image. The uniformity index was calculated following methodology which numerically quantifies the dispersion of punctual density values of the wood around the mean density along the radius. The percentage of the heartwood was higher than the sapwood in all species studied. The density results showed no statistical difference between heartwood and sapwood. Differently from the density results, in all species studied there was statistical differences between uniformity indexes for heartwood and sapwood regions, making justifiable the inclusion of the density uniformity index as a quality parameter for *Eucalyptus* wood.

Key words: gamma radiation, image analysis, *Eucalyptus*, density uniformity index.

INTRODUCTION

Wood is a heterogeneous material formed by a set of cells with specific properties to perform the main functions of water conduction, storage of biochemicals and mechanical support of the plant body. The search for an interpretation increasingly detailed and in-depth of this complex and multifunctional system is a permanent scientific challenge. Today, with the availability of more potential equipments and techniques, themes once studied partially or with limitations, gain new perspectives of analysis.

Wood of most trees can be divided into two distinct regions in terms of their physiological activity: sapwood and heartwood. These regions are identified in many species, although their

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occurrence, properties and color can vary (Hillis 1987).

Quantification of these regions is possible, in some species, by direct visual analysis of the wood due to pronounced differences in color between sapwood and heartwood conferred by the accumulation of extractives. The central portion (heartwood) is darker than the peripheral one (near the bark) which is clearer (sapwood). However, in certain species, despite the existence of heartwood, there are little or almost no visually detected differences between heartwood and sapwood colors. In such cases, identification requires the analysis of differences in the chemical level as a difference in pH between the sapwood and heartwood (Hillis 1987, McKimm 1985, Campbell et al. 1990, Winandy and Morrell 1993, Clarke et al. 1997) or the observation of anatomical features - tyloses may also be used to distinguish heartwood from sapwood but only in species where such features are closely associated with heartwood formation (Bamber and Fukazawa 1985). These authors state that this is the most appropriate method for the *Eucalyptus* genus. The application of X-ray densitometry can also be extremely useful to identify the sapwood - heartwood boundaries, based on different wood properties and levels of X-ray attenuation (Tomazello Filho et al. 2008).

There are marked differences between the heartwood and sapwood, which may be interesting or not, depending on the use of wood. Heartwood contains more extractives than the sapwood (Miranda et al. 2006), higher lignin content (Lachenbruch et al. 2011), and generally, less cellulose and holocellulose (Chen 1991, Shupe et al. 1997). Concerning hemicelluloses, only small differences have been observed between heartwood and sapwood (Holmbom et al. 2000); the heartwood has a lower moisture content due to reduced physiological activity; the heartwood is less permeable and has more compact tissue than the sapwood (Burger and Richter 1991); due to the extractives content of heartwood (which usually increases steadily from pith to periphery of the heartwood) it influences wood density (Kai 1991, Singleton et al. 2003, Grabner et al. 2005, Pillai et al. 2013); the strength is closely correlated with the density, thus strength differences may exist between heartwood and sapwood. However, heartwood does not differ structurally from sapwood; any significant strength differences result from radial changes in wood density and cell wall ultra-structure, not whether the sample is heartwood or sapwood (Panshin and De Zeeuw 1980); the heartwood usually has a higher natural durability due to the absence of nutritious materials (carbohydrates, mainly in the form of starch), and especially to the presence of extractives (Bamber 1981, Oliveira et al. 1986, Wiedenhoeft 2012).

Such anatomical and functional differences promote very different behavior of heartwood and sapwood from both physical and chemical point of view. Wilkes (1991) reports that while the sapwood is preferable for the production of pulp for paper - low content of extractives - the heartwood is used for construction with higher requirements of finishing, furniture industry, for example, due to its characteristics of greater natural resistance.

The variation in the proportion and characteristics of heartwood have been the subject of several reviews and vary with a large number of factors, including species, age, position in the tree, genetics, growth rate, leaf area, environmental parameters, as soil, climate, site quality, tree vitality, and forestry management (Smith et al. 1966, Hillis 1971, 1972, 1984, 1987, Bamber 1976, Panshin and De Zeeuw 1980, Wilkins 1989a, b, Wilkes 1991, Hazenberg and Yang 1991, Yang and Hazenberg 1991, Kort 1992).

The largest density variation within the stem is usually associated with the radial direction, and its measurements suggest possible end uses of wood (Bodig and Jayne 1993). The mean density of the wood can be measured with reasonable accuracy by conventional methods, but its variation within a sample is more accurately measured by radiological methods such as X-ray and attenuation of gamma radiation.

Several authors, in pioneer studies (1970s and 1980s), observed that the basic density values increased from pith to bark for eucalyptus species. For *Eucalyptus grandis* adult trees (23 years old), Oliveira et al. (2012) observed this same tendency. In more recent studies, with younger trees (< 20 years old), Trevisan et al. (2008), Arantes (2009), Pinheiro (2013) and Pereira et al. (2013), reported lower density values in the heartwood region increasing gradually toward the bark reaching maximum values very close to the bark, in sapwood region.

Due to the importance of the proportion of heartwood and sapwood, its density variations as well as uniformity in the use of wood in certain applications and the possibility of using greater potential techniques to deeply differentiate these regions, this study aimed to quantify and physically qualify the wood of heartwood and sapwood of the three species of eucalyptus and suggest a new tool that is not mean density for evaluating the quality of the wood.

MATERIALS AND METHODS

SAMPLING PROCEDURES

Six trees of the following species were selected and harvested from plantation originally established with 2m x 3m planting spacing.

- *Eucalyptus grandis* Hill ex. Maiden (18 years old) provided by the College of Agricultural Sciences of Botucatu are from Lageado Experimental Farm, Botucatu, São Paulo State, Brazil (22º51’55” S; 48º26’22” W);
- *Corymbia citriodora* (28 years old) provided by PREMA Tecnologia e Cormércio Ltda are from Ecological Station Mogi Guaçu, Mogi Guaçu, São Paulo State, Brazil (22º16’50” S; 47º3’19” W);
- *Eucalyptus tereticornis* (35 years old) provided by PREMA Tecnologia e Comécio Ltda are from Casa Grande Farm, Corumbataí, São Paulo State, Brazil (22º13’6” S; 47º31’21” W).

Two disks at breast height (DBH) were obtained from each tree: one for characterization and quantification of heartwood and sapwood and another for the determination of basic and apparent density with the use of attenuation gamma radiation technique. All the disks were peeled, planed in a lathe, and sanded with orbital sander to acquire uniform thickness (20 mm for the disk to quantification of heartwood and sapwood and 30 mm for the disk to attenuation gamma radiation technique); the disks were stored to equilibrium in a climate-controlled room under 65% relative humidity and 21 ºC (approximately 12% EMC – equilibrium moisture content).

DELIMITATION OF THE HEARTWOOD AND SAPWOOD

The cross section of the disks was polished (sequence of sand papers) and analyzed in a stereo-microscope of 10× increase. The heartwood was characterized by the presence of tyloses in the vessels (Figure 1).

The boundary between heartwood and sapwood was marked with a fine-tipped pen and high quality photographs of the disks were obtained using a digital camera (Fujifilm FinePix S2950 14 MP with Fujinon 18x Wide Angle Optical Zoom Lens and 3-Inch LCD) and a black background with the presence of a scale of 1cm^2 (graph paper). Photos were analyzed by digital image processing (computational algorithm in MatLab® platform version 7.12.0 -R2011a) for the determination of total areas of heartwood and sapwood (Figure 2).

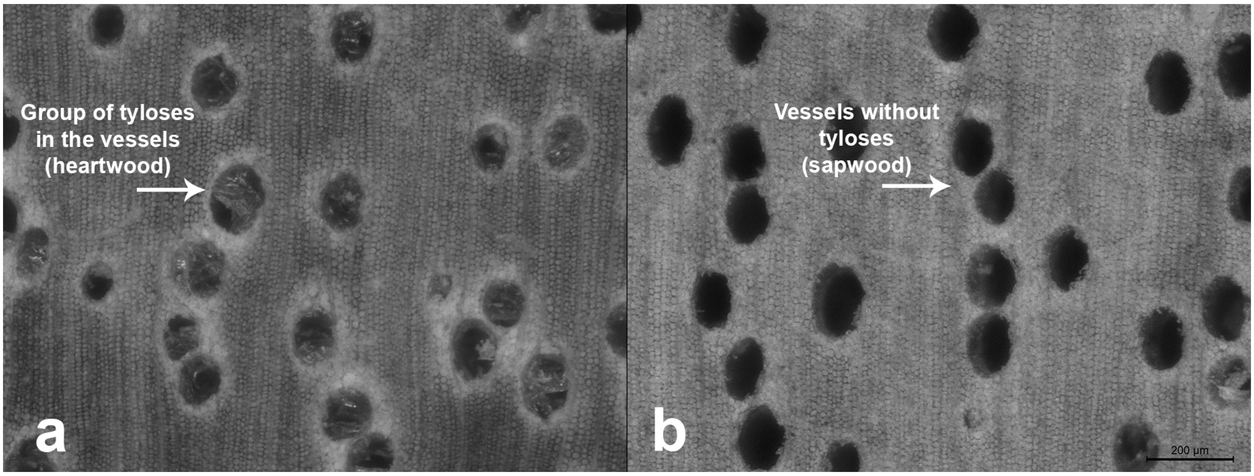

Figure 1 - Vessels observed on the polished cross section of *Eucalyptus grandis* wood (scale: 200µm); **(a)** vessels filled with tyloses, disc area characterized as heartwood; **(b)** vessels without tyloses, disk area characterized as sapwood.

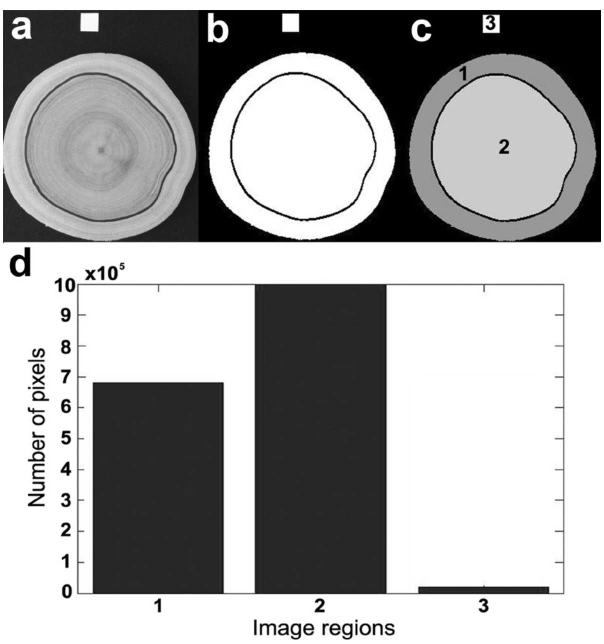

Figure 2 - Example of the stages of digital analysis of the *Corymbia citriodora* disk: **(a)** acquisition of high quality image; **(b)** binarization and highlight of the border of the image; **(c)** separation and recognition of interconnected regions; **(d)** Final histogram for the calculation of areas and percentages of regions.

APPARENT DENSITY (12% MOISTURE CONTENT)

The apparent density of the wood (mass and volume at 12% MC) of the disks was determined by the attenuation gamma radiation technique (Figure 3). For this technique the average radius of the disk was used for the evaluation of density variation in the radial direction of the wood. Although the technique has been applied only to the average radius of the disc, these were kept entirely to facilitate the positioning of the material in the equipment.

This equipment is basically composed of: a radial source with radioisotope ^{241}Am (Rezende et al. 1998, Palermo et al. 2004), a solid scintillation detector system with a crystal of sodium iodide with traces of thallium, a signal conversion board A/D (Analog / Digital) for supplying the values of I and I_0, and an electromechanical apparatus for the automatic movement of the sample - wood disks.

Density was determined by differential absorption of radiation (Parrish 1961, Ferraz and Mansel 1979), i.e., the higher the density, the greater the absorption and the lower the amount of radiation that passes through the absorber material. Equation 1 calculates the punctual density (adaptation to the Beer-Lambert law), with corrections provided by equation 2 and 3 due to the dead time of the electronic system.

$$\rho_U = \frac{\ln(I_{0C} - BG) - \ln(I_C - BG)}{\mu_m \cdot \chi_m} \quad (1)$$

$$I_{0C} = \frac{I_0}{1 - \tau I_0} \quad (2)$$

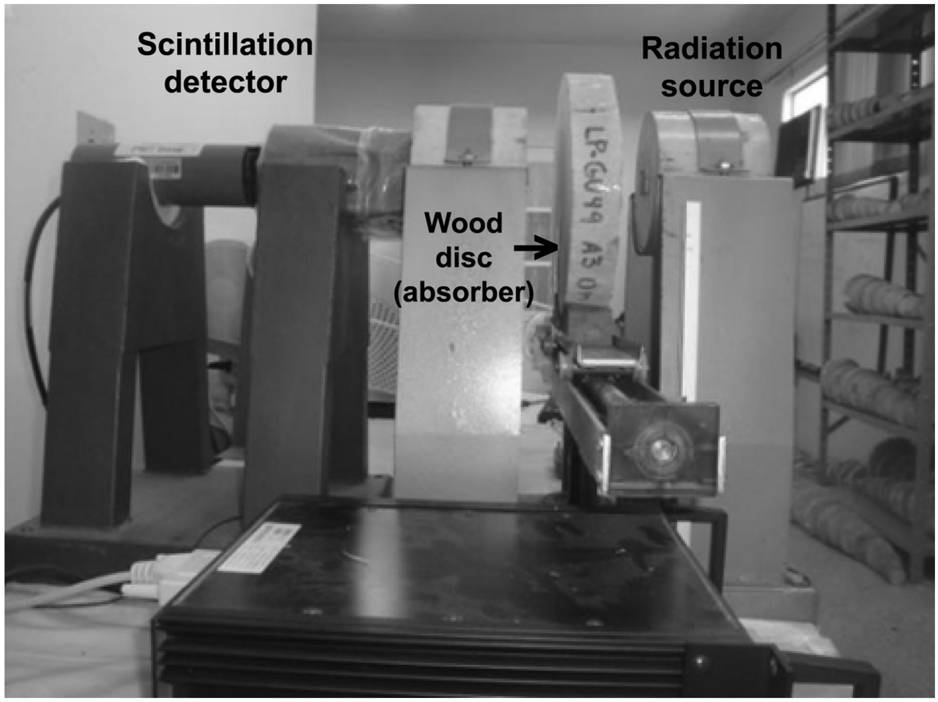

Figure 3 - Attenuation gamma radiation technique (Side detail of the sample movement between the source of radiation emission and the detection system).

$$I_c = \frac{I}{1-\tau I} \quad (3)$$

where ρ_U is the wood density at a given moisture content (U); μ_m is the mass attenuation coefficient of wood, in $cm^2.g^{-1}$; χ_m is the thickness of the wood specimen in cm; BG is the background radiation counts per minute; I_0 is a counting rate (counts per minute) obtained experimentally without absorbing material; I is a counting rate (counts per minute) obtained experimentally after passage through the absorber material (wood); I_{0c} is a I_0 value corrected due to the dead time of the electronic system by Equation 1; Ic is the I value corrected due to the dead time of the electronic system by Equation 2 and τ is the is a dead time electronics system (1.0×10^{-7} minutes).

The disks at EMC were positioned in the equipment and slowly displaced to cross the radiation source at a speed adjusted to take 2 points of attenuation per millimeter across the average radius and construction of the apparent density profile.

Density profiles across the radius of the disks were used for two distinct evaluation methods: weighted mean density of the wood (entire disk) and its fractions (heartwood and sapwood) and calculation of the density uniformity index for wood and for the two fractions (heartwood and sapwood) separately, based on their punctual values in these regions.

The weighted mean density of each region of interest - heartwood and sapwood - was calculated separately using the delimitation of these regions and the assumption that the disk is formed by several thin and concentric rings with constant thickness: at the central region of the disk is the heartwood and, in the peripheral ring is the sapwood. The juxtaposition of rings, one within another, reconstitutes the disc. Knowing the density at one point of each ring, it is assumed that this density is the mean density of the ring. The weighted mean density of the disk is obtained by weighting the point densities in the rings, wherein the weighting factor is the volume of the ring, i.e., the density of the ring with highest volume is more representative in the weighted average value of density.

The weighted mean density was calculated at the EMC of the sample (U) - r_u - and then transformed into weighted basic density (ρ_b) and weighted density at 12% MC (ρ_{12}) by the equations 4, 5 and 6 proposed by Rezende (1997) and Rezende et al. (1998) and applied to *Pinus* and *Eucalyptus*.

$$\rho_0 = \frac{\rho_U}{(1+0,01U\%)\left[(1-0,0013U\%)-0,0050U\%\rho_0\right]} \qquad (4)$$

$$\rho_b = \frac{0,98\rho_0}{1+0,24\rho_0} \qquad (5)$$

$$\rho_{12} = 1,104\rho_0 - 0,067\rho_0^{\ 2} \qquad (6)$$

where ρ_U is the weighted apparent density at U% humidity, ρ_0 is the weighted apparent density at 0% humidity, ρ_b is the weighted basic density and ρ_{12} is the weighted apparent density at 12% moisture content.

The uniformity index (Echols 1973) numerically quantifies the dispersion around the average density of punctual density values of the wood along the region under evaluation of the sample. Using the histogram of punctual densities, taking the class that contain the average - reference class - and its contiguous (upper and lower) with weight 1, to the other classes are assigned incremental weights (2, 3, 4, etc), which increase as they move away from the referential. The uniformity index is obtained by the sum of multiplications of the frequencies of each class by their respective weights. By this methodology, one ideally uniform wood would have only three frequency classes (referential and its two contiguous) and a uniformity index of 100. The higher the index, the lower would be the uniformity of the wood. In this study, for all species, frequency classes with amplitude of 50 kg.m^{-3} were used.

RESULTS

AREAS AND PROPORTIONS IN HEARTWOOD AND SAPWOOD REGIONS

It can be observed (Table I) that heartwood area is larger than the sapwood one for all species and the *Eucalyptus grandis* showed the largest total area among species.

The mean values of the heartwood area (cm²) ranged from 345.5 to 589.8, percentage of heartwood area ranged from 60.8 to 76.0% and the heartwood/sapwood relation ranged from 1.6 to 3.2.

BASIC AND APPARENT WEIGHTED MEAN DENSITIES IN HEARTWOOD AND SAPWOOD

Figure 4 shows the densitometric profile of one disc (*Eucalyptus grandis* - sample no. 6) where it

TABLE I
Mean values (followed by standard deviation) of the area (cm²) and percentage area of the heartwood and sapwood regions and relation heartwood/sapwood of the disks for the species.

Species	Area (cm^2)			Area (%)		Heartwood/ Sapwood
	Heartwood	Sapwood	Disk*	Heartwood	Sapwood	
C. citriodora	345.5 (72.2)	219.9 (39.3)	565.4 (88.7)	60.8 (5.9) ^{bA}	39.2 (5.9) ^{aB}	1.6 (0.4) ^{b}
E. tereticornis	444.4 (48.0)	139.4 (13.7)	583.8 (42.8)	76.0 (3.1) ^{aA}	24.0 (3.1) ^{bB}	3.2 (0.6) ^{a}
E. grandis	589.8 (142.5)	284.6 (58.6)	874.5 (172.2)	66.9 (6.4) ^{bA}	33.1 (6.4) ^{bB}	2.1 (0.6) ^{b}

In the same column, average followed by at least one lowercase same letter do not differ by Tukey test (p <0.05).
In the same line values followed by at least one uppercase letter do not differ by Student's t test (p <0.05).
*Disk means the entire disk (heartwood+sapwood).

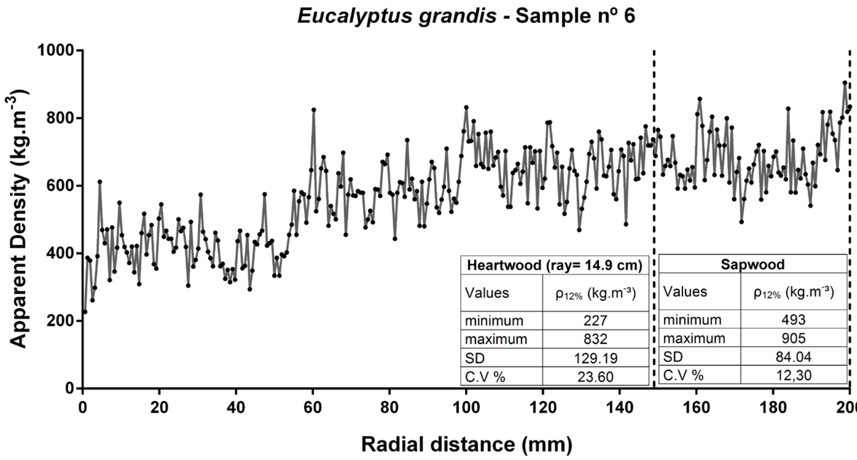

Figure 4 - Densitometry profile (apparent density) of *Eucalyptus grandis*- tree no 6, determined by the attenuation gamma radiation technique.

TABLE II

Weighted basic (ρ_b) and apparent ($\rho_{12\%}$) mean densities (followed by standard deviation) of heartwood and sapwood regions and of the entire disk.

Species	ρ_b (kg.m^{-3})			$\rho_{12\%}$ (kg.m^{-3})		
	Heartwood	Sapwood	Disk	Heartwood	Sapwood	Disk
C. citriodora	721 (34.5) ^{aA}	698 (50.9) ^{aA}	715 (27.9) ^{a}	933 (18.4) ^{aA}	899 (27.0) ^{aA}	924 (41.1) ^{a}
E. tereticornis	703 (59.6) ^{aA}	647 (86.9) ^{abA}	692 (40.4) ^{a}	910 (38.2) ^{aA}	826 (54.9) ^{abA}	892 (59.3) ^{a}
E. grandis	538 (43.5) ^{bA}	593 (60.1) ^{bA}	564 (40.2) ^{b}	672 (62.1) ^{bA}	749 (87.5) ^{bA}	707 (56.1) ^{b}

In the same column, values followed by at least one lowercase same letter do not differ by Tukey test ($p < 0.05$).
In the same line, for the same property, average followed by at least one uppercase do not differ by Student's t test ($p < 0.05$).

can be observed that the maximum and minimum values were higher for sapwood and the coefficient of variation was higher in heartwood.

For all species the weighted mean basic density (Table II) ranged from 538 to 721 kg.m^{-3} in the heartwood region and from 593 to 698 kg.m^{-3} in the sapwood region. Apparent weighted mean density (at mass and volume 12% MC) ranged from 672 to 932 kg.m^{-3} at the heartwood region and from 749 to 899 kg.m^{-3} in the sapwood region.

Wood of *Corymbia citriodora* showed the highest values (both basic and apparent density) of the entire disk and also in the two regions of the wood (heartwood and sapwood), but these values did not differ statistically from the results obtained for *Eucalyptus tereticornis*. *Eucalyptus grandis* was the species that showed lower density, with statistical difference to other species studied for heartwood regions; for the sapwood region, it only statistically differed from *Corymbia citriodora*.

UNIFORMITY INDEX

The uniformity index (Table III) ranged from 187 to 267 in the wood as a whole, from 191 to 258 in the heartwood and from 154 to 157 in the sapwood. The *Eucalyptus grandis* was the species with higher indexes, indicating less uniformity in both heartwood regions and entire disk. However, the sapwood of *E. grandis* had the lowest index.

For all species, sapwood revealed more uniformity (lower index) than heartwood and these results confirm the first impression obtained in a visual analysis. Moreover, it can be noted that heartwood had a greater contribution in the index for the entire disk.

TABLE III
Uniformity index of heartwood and sapwood regions and of the entire disk.

Species	Uniformity index		
	Heartwood	Sapwood	Disk
Corymbia citriodora	195 bA	156 aB	187 bA
Eucalyptus tereticornis	191 bA	157 aB	194 bA
Eucalyptus grandis	258 aA	154 aB	267 aA

In the same column, average followed by at least one lowercase same letter do not differ by Tukey test ($p < 0.05$).
In the same line, average followed by at least one uppercase do not differ by Tukey test ($p < 0.05$).

DISCUSSION

The methods for determining the density of wood by means of the use of X-rays or beta particles, although they present good accuracy, they have limited application for sample thickness. So there is sensitivity in determinations, the average thickness of the samples should not exceed 1.0 cm for X-rays and 2.0 cm for beta ^{90}Sr. However, in many situations, it is necessary to work with thicker samples. In such cases, the use of Gamma radiation has been shown adequate for working with samples ranging from 1.0 to 40.0 cm thickness (Rezende et al. 1999). Therefore, in this study, the attenuation gamma radiation technique was more suitable because of the possibility of using the entire disks with 3.0 cm thickness, in addition, this technique has an easier and faster preparation of the sample.

Long-rotation *Eucalyptus* plantations are specially indicated for timber production considering higher yields in sawmill, increased stability of the wood due to the greater amount of heartwood (Sella 2001, Nawrot et al. 2008) - although the density variability is higher in heartwood than in sapwood (Bossu et al. 2016) - and uniformity in color (Haselein et al. 2004).

In the past, heartwood formation was viewed as an aging process in which a gradual loss of metabolic activity led to cell death, but it is now clear that it defines an active program of tissue senescence. A better understanding is needed of how the loss of conductive function in xylem occurs with age, and how this process differs across species (Spicer 2005).

The results presented in Table I suggest that there is no pattern in heartwood formation correlated with age or size of the trees. The relationships are stronger between growth rate and sapwood width than between growth rate and number of rings in sapwood. That is, the amount of wood needed for physiological process is independent of how that wood was developed (Gartner and Meinzer 2005). Lachenbruch et al. (2011) discuss the radial variation in wood structure and function and state that the particular radial patterns are variable in hardwoods vs. softwoods, and among growth forms, species, environments, and plant parts. The authors have also listed similarities and differences between trees that differ in age but not size, or in size but not age, and it is possible to see that there are numerous candidate functions on which natural selection may have acted, and that there is no one set of similarities or differences from which we can infer why a certain species and trait is more closely correlated with one of the independent variables (age or size) than with the other; there are sets of traits that are most common for a given category of plants.

The largest percentage of heartwood area (and lower percentage of sapwood area) was found in *Eucalyptus tereticornis*, followed by *Eucalyptus grandis*, and finally, *Corymbia citriodora*. Oliveira et al. (1999) in a study of adult trees of seven species of *Eucalyptus* (with approximately 19 years old), found lower percentage of heartwood in the trees of *Corymbia citriodora* compared to *E. grandis* trees, results that coincide with those obtained in this study. Using samples in the basal portion of the main stem, the authors report a mean percentage of heartwood of 51.6 for *Corymbia citriodora*, 67.1 for *E. grandis* and 67.6 for *E. tereticornis*.

Silva (2002) also studied 20 and 25 years old trees of the *Eucalyptus grandis* and observed heartwood and sapwood percentages and heartwood/sapwood relation of 72.4, 27.6 and 2.83 respectively for 20 years old trees. The heartwood percentage and heartwood/sapwood relation are slightly higher than those obtained for the same species in this study.

The mean basic density of *Eucalyptus* was studied by many authors, considering the entire disk (heartwood + sapwood). The relationship between wood density and relation heartwood/sapwood is not a rule, in general, because of the large variability between species and the percentage of juvenile wood, among other factors (Pereira et al. 2013). The evolution of wood density within tree stems varies according to species, following typical radial and longitudinal patterns that are strongly correlated with tree age, size and growth (Lachenbruch et al. 2011).

For young plantations (< 20 years old) of *Eucalyptus grandis* it can be compiled (Table IV) that basic density varied from 424 - 445 kg.m^{-3} – for 6 years old trees (Pillai et al. 2013), 525 kg.m^{-3} – for 10.5 years old trees (Sturion et al. 1987) and varied from 570 - 590 kg.m^{-3} – for 17 - 18 years old trees (Ciniglio 1998, Gonçalez et al. 2006, Lopes et al. 2011). For older plantations (> 20 years old) basic density varied from 690 kg.m^{-3} to 750 kg.m^{-3} – for 20 years old trees (Ashley and Ozarska 2000), suggesting, in general, a direct relation between basic density and age of the trees. In fact, the results here obtained (564 kg.m^{-3}) are very close to those of studies with similar age of the plantations (< 20 years). The apparent densities were 490, 560 to 680 kg.m^{-3} in three different radial positions (inner, intermediate and external, respectively) – for 23 years old trees (Oliveira et al. 2012), indicated increased wood density from pith to bark. The results here obtained, higher than these (Oliveira et al. 2012) also suggested increased wood density in the radial direction (heartwood - 672 kg.m^{-3}; sapwood - 749 kg.m^{-3}) although no statistical differences were observed.

For young plantations (< 20 years old) of *Corymbia citriodora* values of 715 kg.m^{-3} – for 10.5 years old trees (Sturion et al. 1987) and 730 kg.m^{-3} – for 16 years old trees (Oliveira et al. 2005) were obtained for basic density. For older plantations (60 years old) Lourençon et al. (2013) obtained for basic density values from 550 to 820 kg.m^{-3} in 5 positions in radial direction (pith - bark). For apparent density some authors obtained values of 840 kg.m^{-3} – for 23 years old trees (Oliveira et al. 2012), 970 - 1200 kg.m^{-3} for 29 years old trees (Benjamin and Ballarin 2009) and 700 - 860 kg.m^{-3} – for 60 years old trees (Lourençon et al. 2013). The values here obtained were similar to those found in the literature, both to basic density (715 kg.m^{-3}) and apparent density (924 kg.m^{-3}).

For young plantations (< 20 years old) of *Eucalyptus tereticornis*, basic density varies from 592 kg.m^{-3} – for 10.5 years old trees (Sturion et al. 1987) to 660 kg.m^{-3} – for 16 years old trees (Oliveira et al. 2005). The values found by the authors are lower than those obtained here and this inferiority in values probably is associated with younger trees used in their study (16 and 10.5 years old).

For all the species studied, literature reports a tendency of increase in density in the radial direction (pith to bark) which occurred exclusively for *E. grandis* in this study, probably due to the lower age of these trees (< 20 years old). However, for older tress, many authors observed a gradual increase in basic density followed by stability near to the bark (Carmo 1996, Gatto et al. 2010, Lopes et al. 2011, Ribeiro et al. 2011, Lourençon et al. 2013) due to

TABLE IV
Summary table - density values reported in the literature for *E. grandis, E. tereticornis* and *C. citriodora*.

Species	Age (years)	Density ($kg.m^{-3}$)		Reference
		Basic	Apparent	
E. grandis (<20 years)	6	424 - 445	-	Pillai et al. 2013
	10.5	525	-	Sturion et al. 1987
	17-18	570 - 590	-	Ciniglio 1998, Gonçalez et al. 2006, Lopes et al. 2011
E. grandis (>20 years)	28	690 - 750	-	Ashley and Ozarska 2000
	23	-	490 - 680	Oliveira et al. 2012
C. citriodora (<20 years)	10.5	715	-	Sturion et al. 1987
	16	730		Oliveira et al. 2005
C. citriodora (>20 years)	60	550 - 820	-	Lourençon et al. 2013
	23	-	840	Oliveira et al. 2012
	29	-	970 - 1200	Benjamin and Ballarin 2009
	60	-	700 - 860	Lourençon et al. 2013
E. tereticornis (<20 years)	10.5	592	-	Sturion et al. 1987
	16	660	-	Oliveira et al. 2005

changes of the cambial meristem – the wall thickness of fibers is increased and the frequency and number of vessels decreases to supply the mechanical and physiological requirements derived the process of development of trees (Sette Jr et al. 2012).

As introduced in Figure 5, in *C. citriodora* (28 years old) and *E. tereticornis* (35 years old) weighted mean apparent density showed lower variations between heartwood and sapwood compared to *E. grandis* (18 years old). In older trees, heartwood contains a greater amount of mature wood (in comparison with heartwood of younger trees) which promotes increase in densities (Malan 1988, Bao et al. 2001, Passialis and Kiriazakos 2004, Santos et al. 2004, Tomazello Filho 2006, Sette Jr et al. 2010, Oliveira et al. 2012, Bal and Bektaş 2012). Differently, *E. grandis* trees (18 years old) showed lower densities in heartwood and a tendency to increase density along the radius (increase of 11.4% from heartwood to sapwood region) as an effect of the juvenility of wood in these trees. Despite these tendencies, the density showed no statistical difference between heartwood and sapwood.

As reported in Table III, the sapwood presented higher uniformity (≅ 160) in all species studied, which characterizes mature wood. In the heartwood region, great proportions of juvenile wood make the density less uniform and this was particularly observed in the heartwood of *Eucalyptus grandis* (younger trees). In older trees (*E. tereticornis* and *C. citriodora*), despite the difference in homogeneity between heart and sapwood (Table III), heartwood revealed uniformity indexes (191 and 195) closer to those of their respective sapwood regions. In fact, younger trees (*E. grandis*) showed a larger heterogeneity in heartwood (258), due to the fact that most part of it was produced in the juvenile stage of the tree. *E. grandis* showed larger variation (40.3) due to the predominance of juvenile wood as already commented. Differently from the density analyses, in all species studied there was statistical differences between uniformity indexes for heartwood and sapwood regions.

Alzate (2004) found uniformity index of 169.5 for *Eucalyptus grandis.* The uniformity index here obtained (Table III) was higher. These indexes are inferior to those of presented in general by conifers

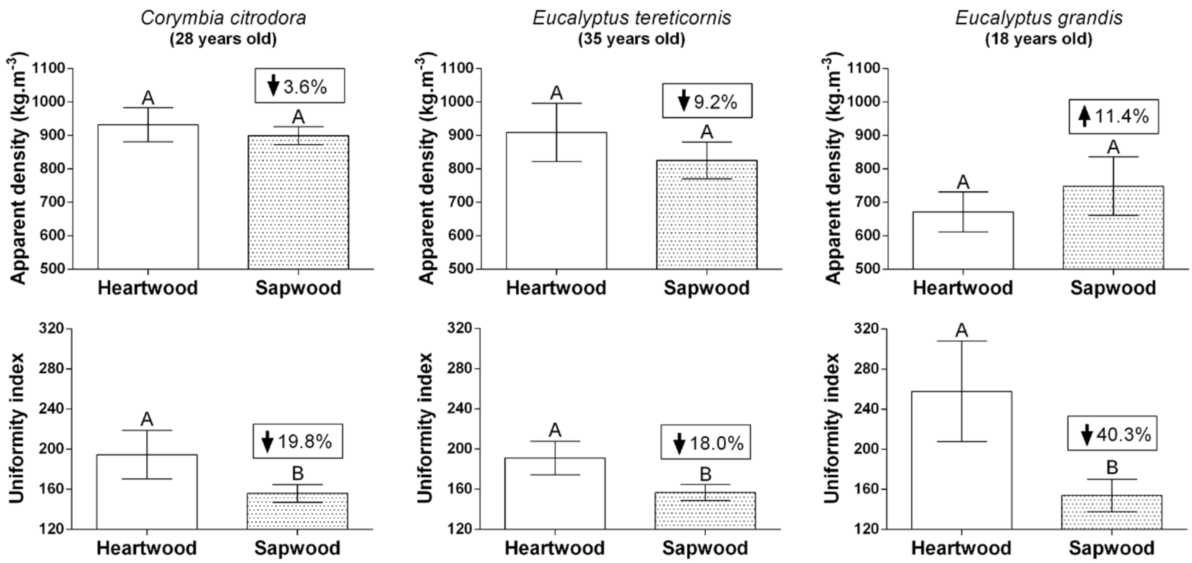

Figure 5 - Histograms of variation in weighted apparent density and uniformity index (with standard deviation) in the heartwood and sapwood of the three species studied.

from temperate climate in which is outstanding the alternation of annual growth rings. Echols (1973) reported uniformity index from 220 to 317 for conifers.

CONCLUSIONS

The percentage of heartwood area was higher in all studied species, and the *Eucalyptus tereticornis* was the specie with the highest percentage of heartwood, followed by *Eucalyptus grandis*, and *Corymbia citriodora*.

The higher basic and apparent density values were found in the *Corymbia citriodora*, followed by *Eucalyptus tereticornis*, and *Eucalyptus grandis*, however, in general, for the trees and species studied from a physical point of view it can be stated that heartwood and sapwood fractions have similar quality in terms of densities, considering that no significant differences were obtained in these properties.

Despite lower areas of sapwood in relation to heartwood, the density is more uniform, possibly due to the greater amount of mature wood, while in the heartwood the amount of juvenile wood makes the density along this fraction less uniform.

The results justify the inclusion of the density uniformity index as a quality parameter for *Eucalyptus* wood, calculated by the applying of the punctual values of apparent density by gamma radiation. This parameter can be considered a very important tool for qualifying wood for timber purposes, but primarily for wood-based composite materials, where the homogeneity of the wood influences intensely on the quality of the final product.

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