# RADIAL VARIATION OF DENSITY AND ANATOMICAL FEATURES OF *EUCALYPTUS NITENS* TREES

## Linette Salvo

Research Associate
Wood Drying Research Group
Department of Wood Engineering
Universidad del Bío Bío, Chile
E-mail: lsalvo@ubiobio.cl

## Laura Leandro

Forest Products Consultant
San José, Costa Rica
E-mail: lalezu76@gmail.com

## Helga Contreras

Research Associate
Department of Wood Engineering
Universidad del Bío Bío, Chile
E-mail: hcontrer@ubiobio.cl

## Alain Cloutier†

Professor
Université Laval, Canadá
E-mail: alain.cloutier@sbf.ulaval.ca

## Diego M. Elustondo

Professor
Luleå Tekniska Universitet, Campus Skellefteå
Forskargatan 1, 93187 Skellefteå, Sweden
E-mail: diego.elustondo@ltu.se

## Rubén A. Ananías*†

Professor
Wood Drying Research Group
Department of Wood Engineering
Universidad del Bío Bío, Chile
E-mail: ananias@ubiobio.cl

(Received November 2016)

**Abstract.** This paper studies the relationship between apparent density and some anatomical properties of *Eucalyptus nitens* such as vessel frequency, vessel area, ring width, fiber cell wall thicknesses, and fiber length. The study involved 29 trees from 10 families of *Eucalyptus nitens* cut from a 17-yr-old plantation in Southern Chile. The properties were determined along the radial direction of the trees by using X-ray equipment and at selected positions through microscope and fiber quality analyzer equipment. The results showed that the anatomical properties of *E. nitens* did not change gradually from pith to bark, but they were better described by dividing the tree radius into three different wood-zones referred to as

* Corresponding author
† SWST member

inner-, middle-, and outer-wood. The apparent density of *E. nitens* was dependent of the vessel area, cell wall area, ring width, and latewood width. The correlation coefficient between apparent density and vessels area was negative and the correlation coefficient between apparent density and cell wall area, latewood ring width, and total ring width were positive. These means that *E. nitens* wood with lower density tended to have higher vessel area, and lower fiber cell wall area, ring width, and latewood width.

## INTRODUCTION

The scientific literature is not always consistent about the differences in wood density depending on the origin of the wood within and between trees of *Eucalyptus nitens*. For example, basic density significantly changed among nine geographical locations in New Zealand (Shelbourne et al 2002) and five locations in South Africa (Purnell 1988), but no significant differences, from 436 to 460 kg/m$^3$, were reported among five locations in Australia (McKimm 1985). In some studies, the basic density increased significantly from the center to the periphery of the trees (McKimm 1985; Hudson et al 1998; Evans et al 2000; Medhurst et al 2012; Rebolledo et al 2013), eg, from 446 to 522 kg/m$^3$ (McKimm 1985), but in a study with 8- and 11-yr-old *Eucalyptus* from New Zealand there were not significant differences depending on the radial position (McKinley et al 2002). Previous studies reported basic densities between 479.6 and 553.4 kg/m$^3$ (512.6 kg/m$^3$ average) in 11-yr-old trees from five different geographical locations in South Africa (Purnell 1988), between 429 and 505 kg/m$^3$ in 15-yr-old trees with three different diameter ranges from New Zealand (Lausberg et al 1995), between 470 and 580 kg/m$^3$ (525 kg/m$^3$ average) in 15-yr-old trees from New Zealand (Evans et al 2000), 440 and 451 kg/m$^3$, respectively, in 8- and 11-yr-old trees (McKinley et al 2002), 452 kg/m$^3$ in 9-yr-old *Eucalyptus* from nine different locations in New Zealand (Shelbourne et al 2002), between 459 and 546 kg/m$^3$ (495 kg/m$^3$ average) in 15-yr-old trees in New Zealand at a height of 6 m with respect to the ground (McKenzie et al 2003), and between 495 and 659 kg/m$^3$ (580 kg/m$^3$ average) in 15-yr-old trees from two different geographical locations in New Zealand (Kibblewhite et al 2004).

The average basic density also increased significantly from the bottom to the top of the trees in 15-yr-old *E. nitens* trees (Leandro et al 2008), in 9-yr-old trees (Mariani et al 2006), and among 15-yr-old trees sorted in three different diameter ranges (Lausberg et al 1995). It was also showed that ring density increased from inner- to outer-wood due to a decrease of total ring width (Ananías et al 2014). Some studies mentioned that the middle-wood between the center and the periphery of the tree was more prone to internal intraring checks (Leandro et al 2008) and collapse (Ananías et al 2014), and the intensity of intraring checks increased in wood with wider annual rings and lower density (Rebolledo et al 2013). However, no collapse and internal intraring checking were observed during drying of *E. nitens* at low temperature (Sepulveda et al 2016).

Studies to characterize the anatomical properties of *E. nitens* have been performed in Australia (McKimm 1985; McKimm and Ilic 1987; Hudson et al 1998), South Africa (Purnell 1988), New Zealand (Lausberg et al 1995; Evans et al 2000; Kibblewhite and Riddell 2000; Kibblewhite et al 2004a; McKinley et al 2002; Shelbourne et al 2002; McKenzie et al 2003), and Chile (Leandro et al 2008; Rebolledo et al 2013). It was found that radial variation of wood properties is affected by cambial age, conductivity-storage changes, and mechanical support requirements of trees (Zobel and van Buijtenen 1989; Schweingruber 2007; Lachenbruch et al 2011). Density and ring-width radial pattern reflects cambial activity as function of environmental conditions; as if a tree genotype responds to the environmental conditions that it would be interpreted as a measure of the tree phenotype plasticity (Fichtler and Worbes 2012). It was reported that from pith to bark, the size of the

vessels increases, but the frequency of vessels and total ring width decreases (McKimm and Ilic 1987; Lausberg et al 1995; Hudson et al 1998; Medhurst et al 2012). It was also showed that the vessels frequency and the vessels area increased form the bottom to the top of the trees (Hudson et al 1998). A preliminary study with one 15-yr-old tree in Chile performed by cutting samples every 5 m (to a total height of 25 m) showed that the frequency and size of the vessels and the cell wall thickness increased with the height, whereas the diameter of the fibers tended to reduce (Leandro et al 2008). It was reported that the radial position of the wood with respect to the center of the tree was associated to an increase in the size of the vessels and the length of the fibers (McKimm and Ilic 1987), a reduction in the frequency of vessels (McKimm and Ilic 1987; Lausberg et al 1995; Hudson et al 1998), and a reduction of the annual ring width (Medhurst et al 2012; Rebolledo et al 2013). A study with 9-yr-old trees from Chile showed an increase in the frequency of vessels and hemicellulose content with the height, a reduction in the size of the vessels and the lignin content, and no significant differences in the proportion of fibers (Mariani et al 2006).

Some values reported in the literature for the size of the vessels in the radial and tangential directions were 122 and 103 μm, respectively, and the frequency of the vessels were 15 per mm$^2$ (McKimm and Ilic 1987). For the fiber length, cell diameter, and wall thickness, some values reported in the literature were 630, 8.1, and 3.6, respectively, in 8.5-yr-old trees from Australia (McKimm and Ilic 1987), and 860, 13.2, and 6.9 in 15-yr-old trees from New Zealand (Kibblewhite and Riddell 2000). It is also known that wood density can be manipulated by silvicultural practices and breeding tree selection (Zobel and van Buijtenen 1989; Saranpää 2003). In particular, wood density is a key factor in the manufacture of solid wood products from *E. nitens*. Wood density is a critical factor in drying of solid wood products due to collapse (Ananías et al 2014) and internal intraring checks in lower density *E. nitens*

boards (Rebolledo et al 2013). It is argued, therefore, that the higher incidence of collapse and internal checks in middle-wood may be caused by differences in the anatomical properties among core-, middle-, and outer-wood. Consequently, the objective of this study is to determine if there are differences in the anatomical properties of *E. nitens* wood as function of the radial position with respect to the pith.

## MATERIALS AND METHODS

The trees for this study were obtained from a plantation of *E. nitens* in the commune of Yungay, located in the VIII Region of Bio-Bio, Chile (37°15′ S, 71°55′ O). The plantation was 17-yr-old and contained trees with 10 different genetic backgrounds (referred as families in this document). Three trees were selected for each family, with the exception of one family for which there were only two trees available (a total of 29 trees). Two successive 7- and 3-cm-thick disks were cut from each tree at the diameter of breast height. From each disk, a central board pointing in the direction of the north was selected for measuring the anatomical properties listed in Table 1.

The first disk was used to measure the diameter and frequency of the vessels, the cell lumen diameter and the cell wall thickness of the fibers in the radial and tangential direction. For these measurements, each central board was cut approximately in the middle (through the pith) to obtain two matched boards from each disk, and then each matched board was divided into three different zones along the radial direction (Fig 1a). These zones were defined as inner-wood (between the pith and the annual ring number 5), middle-wood (between annual rings number 6 and 10), and outer-wood (between annual rings number 11 and 17). This definition was based on previous studies suggesting that middle-wood was apparently more susceptible to internal checks and collapse (Leandro et al 2008; Ananías et al 2009, 2014; Rebolledo et al 2013). Finally, two 2 cm × 2 cm × 2 cm cubes were cut for each zone from each matched

Table 1.   Summary of measured parameters and experimental design.

| Parameters | Nomenclature | Units | Families | Trees[a] | Zones | Replicas |
|---|---|---|---|---|---|---|
| Cell wall thickness | wt | μm | 10 | 3 | 3 | 4 |
| Lumen diameter | ld | μm | 10 | 3 | 3 | 4 |
| Fiber length | fl | μm | 10 | 3 | 3 | 1 |
| Vessel diameter | vd | μm | 10 | 3 | 3 | 4 |
| Vessel frequency | vf | no/mm$^2$ | 10 | 3 | 3 | 4 |
| Earlywood density | de | kg/m$^3$ | 10 | 3 | 3 | 1 |
| Latewood density | dl | kg/m$^3$ | 10 | 3 | 3 | 1 |
| Apparent density | da | kg/m$^3$ | 10 | 3 | 3 | 1 |

   wt, thickness of the fiber walls; ld, internal diameter of the fibers; vd, internal diameter of the vessels; fl, length of the fibers; vf, vessel frequency; de, early-wood apparent density; dl, latewood apparent density; da, average apparent density.

   [a] With the exception of one family represented by two trees.

board, thus resulting in 4 cubes per zone. One set of cubes was used for measuring the diameter and frequency of vessels and the second set of cubes was used for fiber length measurements; 160 measures per zone of each anatomical feature were performed.

A total of 10 thin slices for microscope measurement were obtained from the transversal faces of each cube. The procedure is described in the previous literature (Hoadley 1995; Chaffey 2002; Schweingruber 2007). In simple words, the wood is softened, cut into thin slices with a microtone, bleached, and washed. After a preliminary visual selection, the slices are dehydrated, stained, and placed in the microscope. The images (1583 × 0909 mm$^2$) from the microscope are then recorded by a digital camera and analyzed with a commercial piece of software (Wincell Pro, Regent Instruments Inc, Canada). The remaining material from the cubes was grounded into a fine powder and run through a commercial Fiber Quality Analyzer (OpTest Equipment Inc, Canada) for measuring the fiber

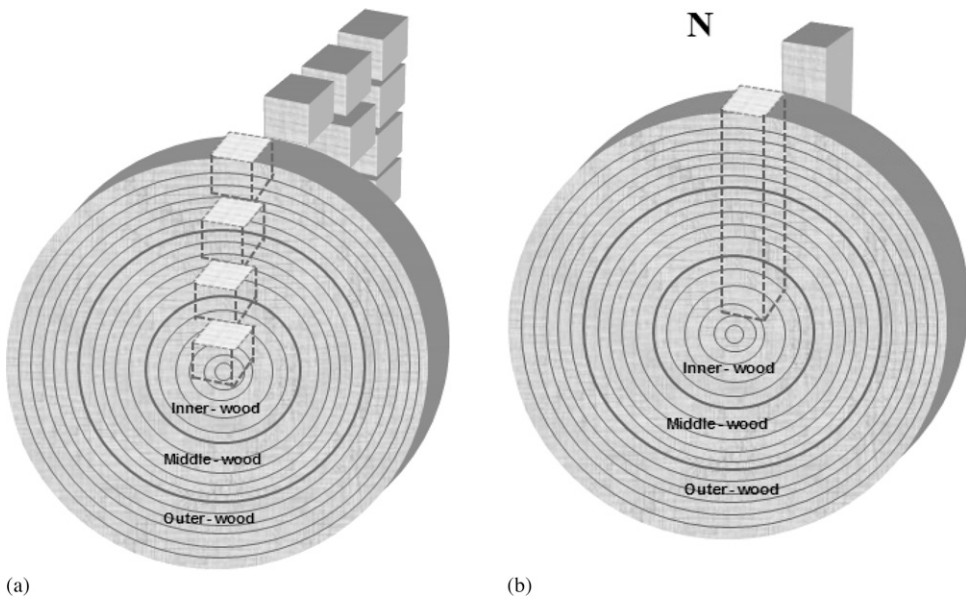

(a)                                          (b)

Figure 1.   Location of the samples according to the definition of inner-, middle-, and outer-wood. (a) For vessels and fibers. (b) For ring-width and density.

length (based on 5500 fibers per cube). From the image analysis data the average internal diameter of the fibers (ld) and vessels (vd) as well as the thickness of the fiber walls (wt) were determined in the radial (r) and tangential (t) directions. From these data the average vessel area ($A_v$) and the fiber cell wall area ($A_{fcw}$) were calculated through Eqs 1 and 2:

$$A_v = \pi \cdot \frac{vd_t}{2} \cdot \frac{vd_r}{2} \tag{1}$$

$$A_{fcw} = 2 \cdot wt_t \cdot ld_t + 2 \cdot wt_r \cdot ld_r + 4 \cdot wt_t \cdot wt_r \tag{2}$$

The second disk was used to measure apparent density profile, total ring width, and latewood ring width (Fig 1b), where apparent density was defined as the density of the wood conditioned in a climate chamber (Binder KBF115, Germany) at 20°C temperature and 70% of relative humidity to 12% of MC. The boards after conditioning were resawn into 2 cm wide by 1.7 mm thick strips representing the entire radius of the disks, and then measured with an X-Ray Quintek Data Analyzer (Quintek Measurement Systems, Inc., Knoxville, TN) to determine apparent density profile, total ring width, and latewood ring width. The average apparent density for earlywood and latewood was calculated as the average of the minimum and maximum apparent density values measured along each strip.

The analysis of variance (ANOVA) at 95% confidence level was applied for detecting statistical differences among tree families and radial position of the wood with respect to the pith. In cases in which the null hypothesis was rejected by the ANOVA test, the Tukey's multiple comparison tests at 95% confidence level was applied. The normality of the data and the homogeneity of the variance were also confirmed. In addition, the Pearson's correlation matrix method was used to determine if there were statistically significant effects of the anatomical properties in the density of the wood. The Person test was implemented with commercial software (Statgraphics, Centurion 16.2, Statpoint Technologies, Inc., The Plains, VA).

## RESULTS AND DISCUSSION

Figure 2 shows three examples of apparent density and ring width profiles representative of the measured *E. nitens* trees. Figure 2a, 2b, and 2c represents the average of, respectively, 12, 10, and 7 trees that showed similar trends. Regarding the annual rings, three zones can be identified in all figures: 1) inner-wood (the first five rings) in which ring width and earlywood width decrease from the pith to the middle of the zone and then increase toward the end of
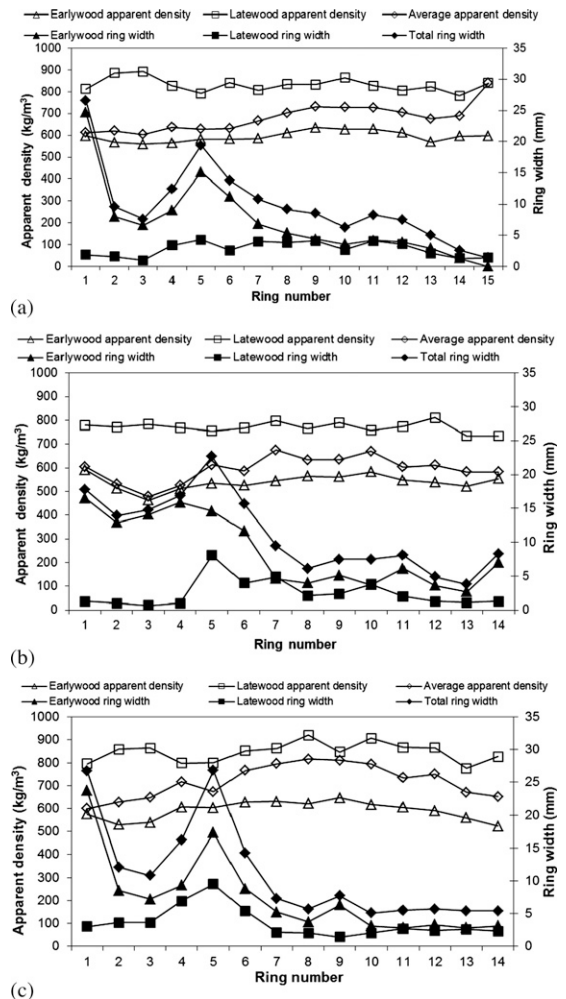


Figure 2. X-ray profile of apparent density and ring-width of some representatives *Eucalyptus nitens* trees. (a) Tree 625. (b) Tree 643. (c) Tree 687.

the zone. In the inner-wood, latewood width starts considerably lower and tends to increase throughout the zone, 2) middle-wood (from 6 to 10 rings) in which ring width and early-wood width rapidly decrease as the ring number increases, and 3) outer-wood (>10 rings) in which ring width and early wood width are relatively constant, and the latewood width becomes more important in terms of its contribution to the total ring width.

Regarding the apparent density profiles, each figure shows slightly different trends: 1) Fig 2a shows that the total apparent density increases constantly from inner- to outer-wood, 2) Fig 2b shows that the total apparent density first decreases through the inner-wood, then increases through the middle-wood, and finally decreases through the outer-wood, and 3) Fig 2c shows that the total apparent density reaches maximum in the middle-wood. Earlywood apparent density showed a similar behavior than total apparent density, but latewood apparent density showed a more oscillating behavior in all cases.

In round numbers, Fig 2 shows that total apparent density ranged approximately between a minimum of approximately 500 kg/m$^3$ in inner-wood (Fig 2b) and a maximum of approximately 800 kg/m$^3$ in inner- (Fig 2c) and outer-wood (Fig 2a). It can also be observed that the apparent earlywood density ranged approximately between 500 and 600 kg/m$^3$, and apparent late wood density ranged approximately between 800 and 900 kg/m$^3$. A different study (Knapic et al 2014) reported that apparent density of *E. nitens* varies from 500 kg/m$^3$ in earlywood to 700 kg/m$^3$ in latewood (600 kg/m$^3$ average). The fact that earlywood and latewood apparent density profiles are more constant in than the total apparent density profiles indicates that the variations in total density are more related to the position of early and latewood within the growth rings than to the anatomical properties of early and latewood independently. Figure 2 also shows a considerably decrease of ring width throughout the middle-wood, which it may explain the different behavior of middle-wood during drying (Ananias et al 2014).

Table 2.  Parameters' average values and standard deviations grouped by tree family.

| Parameters | Families | | | | | | | | | | p value |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
| wt-r | 2.3 (0.3) | 2.5 (0.4) | 2.3 (0.4) | 2.6 (0.4) | 2.3 (0.3) | 2.3 (0.4) | 2.3 (0.4) | 2.2 (0.4) | 2.2 (0.3) | 2.2 (0.3) | <0.05 |
| wt-t | 2.6 (0.3) | 2.7 (0.4) | 2.6 (0.4) | 2.7 (0.4) | 2.5 (0.3) | 2.5 (0.4) | 2.5 (0.3) | 2.5 (0.3) | 2.4 (0.3) | 2.5 (0.3) | <0.05 |
| ld-r | 10.6 (2.5) | 11.6 (2.8) | 11.4 (2.8) | 10.9 (3.1) | 11.5 (2.8) | 11.0 (2.9) | 11.9 (2.7) | 11.6 (3) | 11.1 (2.7) | 10.8 (2.7) | <0.05 |
| ld-t | 13.3 (2.9) | 14.5 (3) | 14.4 (3) | 14.2 (3.3) | 13.9 (3.1) | 12.5 (3.2) | 14.2 (2.8) | 14.3 (3.2) | 13.8 (2.9) | 12.9 (3) | <0.05 |
| vd-r | 137.4 (31.8) | 137.1 (32.8) | 145.6 (24.7) | 142.7 (38.2) | 139.8 (33.8) | 131.6 (37) | 148.6 (32.2) | 133.6 (28.8) | 136.7 (34.7) | 125.9 (28.6) | <0.05 |
| vd-t | 223.7 (52) | 240.9 (62.6) | 237.1 (47) | 243.7 (61.2) | 247.0 (62.5) | 226.3 (68.4) | 238.8 (53.3) | 224.3 (49) | 231.9 (67.3) | 221.7 (51.9) | <0.05 |
| vf | 7.8 (3.1) | 8.9 (2.8) | 8.4 (1.9) | 7.4 (2.1) | 7.8 (2.7) | 8.3 (2.7) | 7.8 (2.5) | 8.8 (2.8) | 9.1 (2.7) | 9.0 (2.7) | >0.05 |
| fl | 693.2 (399.1) | 575.0 (340) | 631.7 (354) | 635.6 (381.6) | 639.5 (347.1) | 652.5 (369.9) | 649.3 (416.9) | 569.1 (351.7) | 661.1 (365.4) | 645.0 (350.5) | <0.05 |
| de | 556.4 (55.7) | 561.0 (60.5) | 546.5 (47.8) | 629.5 (137.7) | 543.1 (16.9) | 574.2 (30) | 579.5 (36.1) | 579.6 (48) | 573.8 (26.1) | 586.1 (35.5) | <0.05 |
| dl | 850.3 (30.5) | 804.0 (50) | 852.5 (34.5) | 754.6 (88.5) | 788.0 (18.9) | 828.0 (42) | 820.1 (16) | 816.9 (31.6) | 824.7 (25.2) | 835.3 (32.1) | <0.05 |
| da | 645.7 (98.5) | 642.5 (120.8) | 633.0 (96.1) | 598.8 (66) | 598.2 (36.4) | 679.2 (81.2) | 668.0 (51.4) | 675.3 (90.2) | 658.1 (44.4) | 702.3 (76.9) | <0.05 |

r, radial; t, tangential; wt, thickness of the fiber walls; ld, internal diameter of the fibers; vd, internal diameter of the vessels.

Table 3. Parameters' average values and standard deviations grouped by type of wood.

| Parameters | Inner | Middle | Outer | Mean | $p$ value |
|---|---|---|---|---|---|
| | | Types of wood | | | |
| wt-r | 2.3 (0.4) | 2.3 (0.4) | 2.3 (0.4) | 2.3 (0.4) | >0.05 |
| wt-t | 2.6 (0.4) | 2.6 (0.4) | 2.5 (0.4) | 2.6 (0.4) | <0.05 |
| ld-r | 11.0 (2.8) | 11.4 (2.9) | 11.3 (2.7) | 11.2 (2.8) | <0.05 |
| ld-t | 13.8 (3.2) | 13.8 (3) | 13.9 (3) | 13.8 (3.1) | >0.05 |
| vd-r | 108.0 (22.5) | 145.9 (26.4) | 159.5 (25.4) | 137.8 (33) | <0.05 |
| vd-t | 180.6 (37) | 246.1 (47.7) | 272.6 (45.7) | 233.1 (58.4) | <0.05 |
| vf | 10.1 (2.4) | 8.1 (2.4) | 6.9 (2) | 8.3 (2.6) | <0.05 |
| fl | 444.9 (226.6) | 736.5 (428.9) | 724.2 (447.3) | 635.2 (367.6) | <0.05 |
| de | 544.0 (65.2) | 588.5 (57.8) | 589.5 (50.7) | 574.0 (61.3) | <0.05 |
| dl | 809.7 (55.8) | 821.2 (46.4) | 824.5 (44.5) | 818.4 (49) | <0.05 |
| da | 584.3 (61.6) | 679.3 (85.5) | 692.1 (54.7) | 651.9 (83.3) | <0.05 |

r, radial; t, tangential; wt, thickness of the fiber walls; ld, internal diameter of the fibers; vd, internal diameter of the vessels.

Table 2 shows the average measured properties (and standard deviations) grouped by the family of precedence. The table indicates that for almost all measured properties (with the exception of the frequency of vessels), the ANOVA test showed that $p < 0.05$, meaning that there were significant differences in anatomical properties among some families. Significant differences in anatomical properties among 14 families of *E. globulus* were also reported in trees from the VIII Region of the Bio-Bio, Chile (Ramírez et al 2009).

Table 3 reports the measured properties (and standard deviations) grouped by the type of wood. For the average of all families and all types of wood the vessel frequency was 8 no/mm², the radial and tangential vessel diameters were 137 and 233 μm, the radial and tangential wall thicknesses were 2.3 and 2.6 μm, the radial and tangential lumen diameters were 11.2 and 13.8 μm, the fiber length was 635 μm, and the earlywood, latewood, and average density at 12% MC were 574, 818, and 652 kg/m³, respectively.

Finally, the ring width, latewood width, cell wall, and vessel area are reported in Table 4. The property with the largest variation with respect to the wood zone was the total ring width, which decreased from 14.5 to 4.9 mm, respectively, from inner- to middle-wood. This results, reflects the cambial plasticity of *E. nitens* trees.

The diameter and frequency of the vessels also changed considerable among inner-, middle-, and outer-wood. Figure 3 shows that the diameter of the vessels (Fig 3a and 3b) changed approximately in the same proportion but opposite direction than the frequency of the vessels (Fig 3c). It can be observed for example, that the radial vessel diameter increased from approximately 140 μm in inner-wood to 190 μm in outer-wood, with a maximum of approximately 240 μm in inner-wood, whereas the frequency of the vessels reduced from approximately 10 n°/mm² in inner-wood to 8 n°/mm² in outer-wood, with a minimum of approximately 7 n°/mm² in inner-wood. The low vessel frequency may also result in a relatively lower moisture

Table 4. Calculated parameters average values and standard deviations grouped by type of wood.

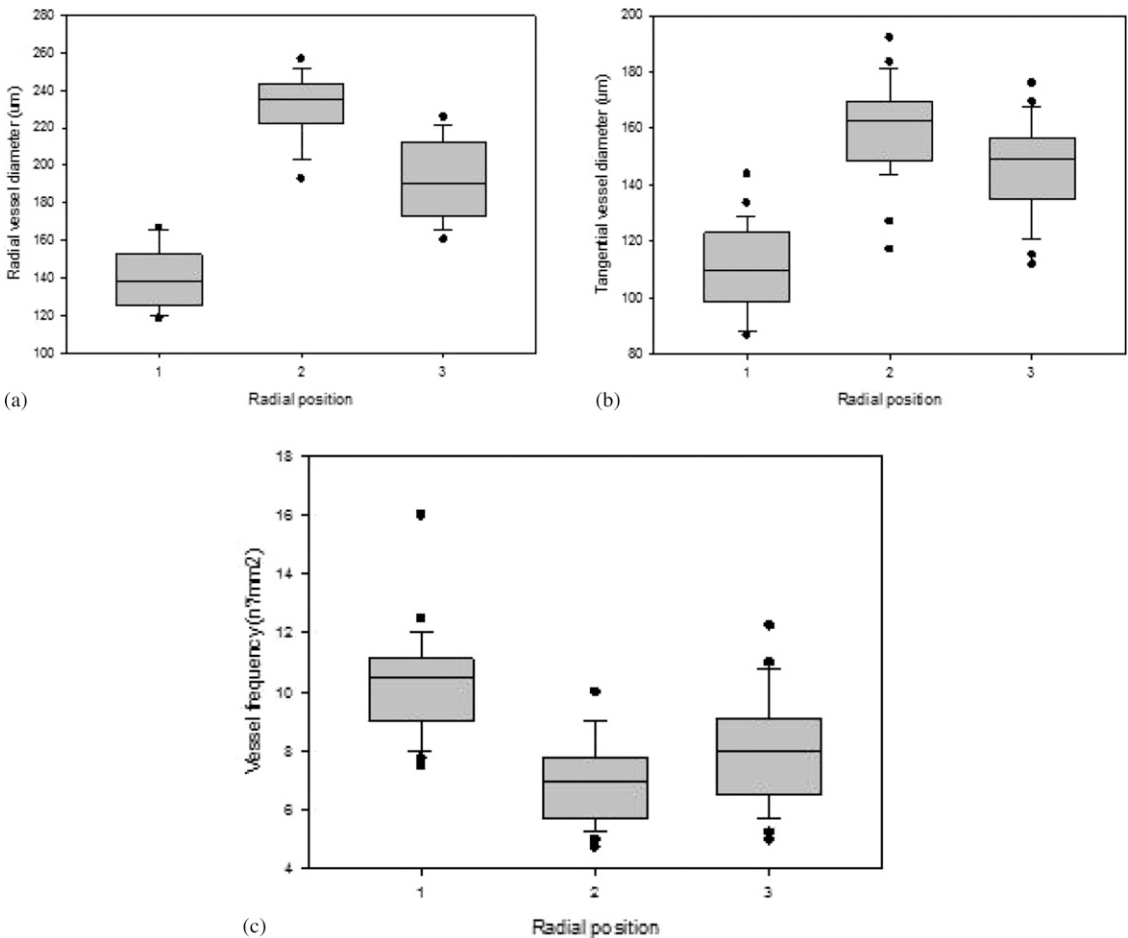| Property | Inner | Middle | Outer | Mean | $p$ value |
|---|---|---|---|---|---|
| | | Types of wood | | | |
| Vessel area | 0.016 (0.005) | 0.031 (0.011) | 0.037 (0.011) | 0.028 (0.009) | <0.05 |
| Cell wall area | 65.4 (12.5) | 67.0 (12.6) | 66.2 (12.3) | 66.2 (12.5) | <0.05 |
| Ring width | 13.5 (2.9) | 8.7 (2.4) | 4.9 (1.7) | 9.0 (2.3) | <0.05 |
| Latewood width | 2.0 (0.8) | 3.1 (1.3) | 2.4 (0.8) | 2.5 (1.0) | <0.05 |

Figure 3. Vessel diameter and frequency as function of the type of wood. (a) Radial vessel diameter. (b) Tangential vessel diameter. (c) Vessel frequency.

conductivity in the transition zone of *E. nitens* trees, which typically shows more intense internal intraring checks during drying (Rebolledo et al 2013).

The ANOVA tests indicated that most properties significantly changed with the type of wood ($p < 0.05$), with the exception of the cell wall thickness in the radial direction and the lumen diameter in the tangential direction (Table 3). The property with the largest variation with respect to the type of wood was the fiber length, which increased from 444.9 to 736.5 μm, respectively, from inner- to middle-wood. Figure 4 shows the contrast between

fiber length (that increased considerably from inner- to middle-wood) and the average cell wall thickness and lumen diameter (that remained relatively constant). The vessels area and cell wall area also changed significantly from inner- to middle-wood (Table 4). In average, the vessels area increased from 0.016 to 0.037 mm$^2$ and the cell wall area increased from 65.4 to above 66.2 um$^2$ from inner- to outer-wood. In comparison, Hudson et al (1998) reported that vessels area in the radial directions increased from 0.005 to 0.035 mm$^2$, and Ramírez et al (2009) found significant differences in vessels area from pith to bark in *E. globulus* trees from the VIII Region of the Bio-Bio, Chile.
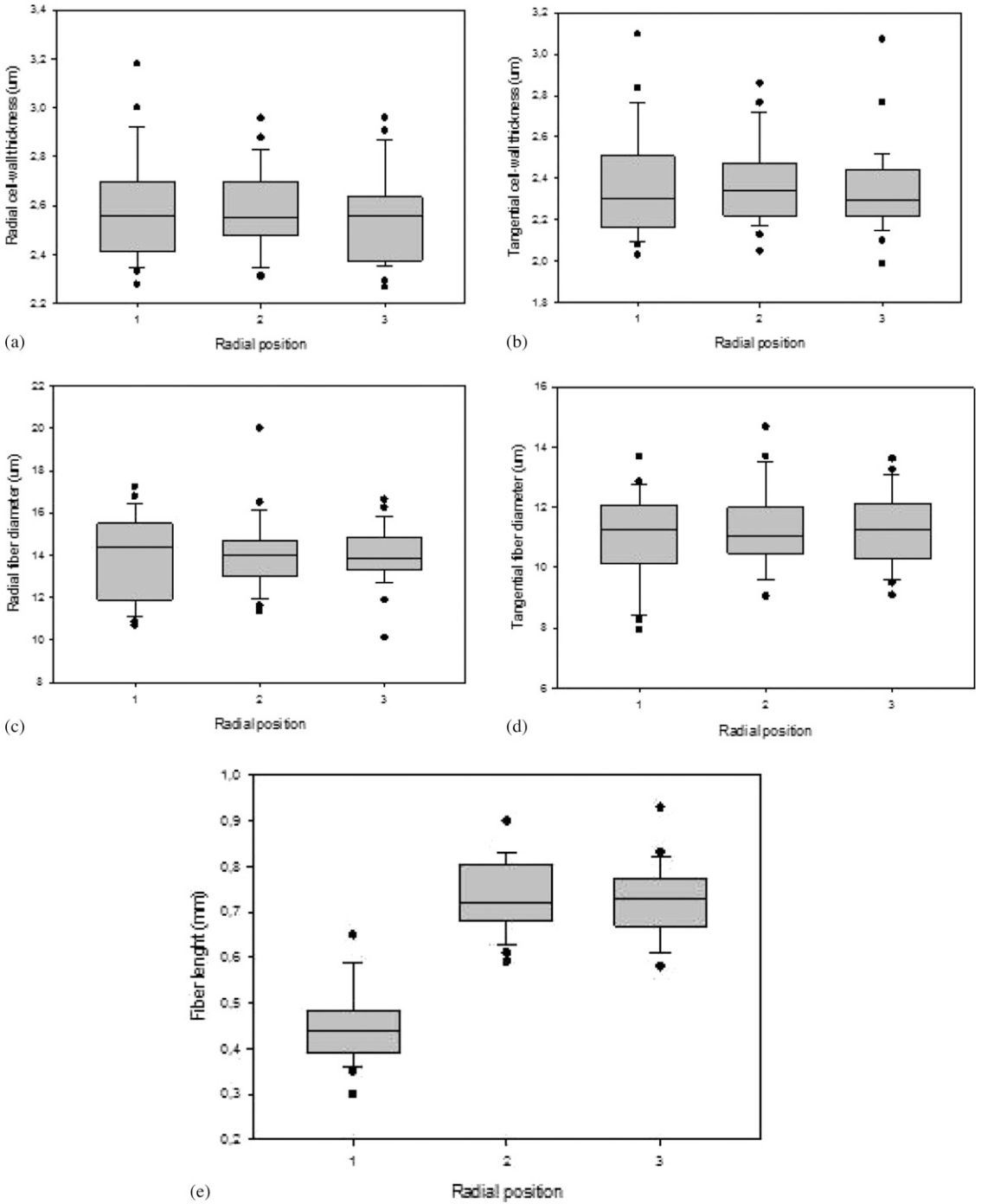
Figure 4. Fiber length, cell wall, and lumen diameter as function of the type of wood. (a) Radial cell wall thickness. (b) Tangential cell wall thickness. (c) Radial fiber diameter. (d) Tangential fiber diameter. (e) Fiber length.

Table 5.  Significant relationships between apparent density and anatomical parameters according to Pearson's test.

| Apparent density | Vessel area | Cell wall area | Latewood width | Ring width |
|---|---|---|---|---|
| Inner | −0.9927* | 0.9862* | 0.9875* | 0.9259* |
| Middle | −0.9867* | 0.9906* | 0.9702* | 0.9704* |
| Outer | −0.9844* | 0.9930* | 0.9860* | 0.9711* |

*$p < 0.05$.

McKimm and Ilic (1987) found no significant differences of vessel area between provenances of *E. nitens* trees.

The Pearson's test was applied to confirm whether there were statistically significant differences between the density and the calculated anatomical properties of the wood. The results are reported in Table 5. The table indicates that the density of *E. nitens* was dependent of the vessel area, cell wall area, ring width, and latewood width. The table also shows that the correlation coefficient between apparent density and vessels area was negative (with r values of −0.997, −0.986, and −0.984 for, respectively, inner-, middle-, and outer-wood) and the correlation coefficient between apparent density and cell wall area, latewood ring width, and total ring width were positive. These means that *E. nitens* wood with lower density tended to have higher vessel area, and lower cell wall area, ring width, and latewood width.

## CONCLUSIONS

This study reports radial variations of apparent density related with wood anatomical properties in *E. nitens*. The data showed that the average apparent density of *E. nitens* decreased with the vessel area and increased with the cell wall area, ring width, and latewood width. Among tree families all measured properties presented significant differences except the frequency of vessels. The most important finding of this study, however, is that within trees some of the anatomical properties of *E. nitens* did not change gradually from pith to bark. On the contrary, some properties were better described by dividing the tree radius into three different wood-zones referred as inner-, middle-, and

outer-wood. It was found for instance that vessels diameter and vessels frequency are higher and lower in middle-wood, respectively, and the average density and earlywood density reduce sharply through the middle-wood (from a maximum that occurs close to the inner-wood). The results agree with previous studies showing that the drying behavior of *E. nitens* is different for middle-wood, which tend to develop a higher collapse and intraring checks during drying. Of course, more research in needed to demonstrate whether differences in the anatomical properties of middle-wood can explain the higher incidence of collapse and internal checks, but it is clear from the results of this study that middle-wood should be treated as a different type of wood, both because of its drying behavior and anatomical properties.

## REFERENCES

Ananías RA, Sepúlveda V, Pérez P, Leandro L, Salvo L, Salinas C, Cloutier A, Elustondo DM (2014) Collapse of *Eucalyptus nitens* wood after drying depending on the radial location within the stem. Dry Technol 32(14): 1699-1705.

Ananías RA, Díaz C, Leandro L (2009) Preliminary study on shrinkage and collapse in *Eucalyptus nitens* [in Spanish]. Maderas Cienc Tecnol 11(3):251-262.

Chaffey N (2002) Wood microscopical techniques. Pages 17-40 *in* N Chaffey, ed. Wood formation in trees. Chapter 3. Taylor & Francis, New York, NY.

Evans R, Kibblewhite RP, Stringer SL (2000) Variation in microfibril angle, density and fiber orientation on twenty-nine *Eucalyptus nitens* trees. Appita J 53(6): 450-457.

Fichtler E, Worbes M (2012) Wood anatomical variables in tropical trees and their relation to site conditions and individual tree morphology. IAWA J 33(2): 119-140.

Hoadley B (1995) Wood accurate results with simple tools. Taunton Press. Newton, CT.

Hudson I, Wilson L, van Beveren K (1998) Vessel and fibre property variation in Eucalyptus globulus and

*Eucalyptus nitens*: some preliminary results. IAWA J 19(2):111-130.

Kibblewhite RP, Riddell MJC (2000) Wood and kraft property variation among the logs of nine trees of *Eucalyptus nitens.* Appita J 53(3):237-244.

Kibblewhite RP, Evans R, Riddell MJC, Shelbourne CJA (2004). Changes density and wood-fibre properties with height position in 15/16-year-old *Eucalyptus nitens* and *E. fastigata.* Appita J 57(3):240-247.

Knapic S, Pirralho M, Louzada J, Pereira H (2014) Early assessment of density features for 19 *Eucalyptus* species using X-ray microdensitometry in a perspective of potential biomass production. Wood Sci Technol 48(1):37-49.

Lachenbruch B, Moore JR, Evans R (2011) Radial variation in wood structure and function in woody plants, and hypotheses for its occurrence. Pages 121-164 *in* Meinzer F, Lachenbruch B, Dawson TE (eds) Size and age related changes in the tree structure and function. Tree physiology, Vol 4, Springer, New York, NY.

Lausberg MJF, Gilchrist KF, Skipwith H (1995) Wood properties of *Eucalyptus nitens* grown in New Zealand. N Z J For Sci 25(2):147-163.

Leandro L, Ananías R, Cloutier A, Díaz-Vaz JE, Bermedo M, Sanhueza R, Lasserre JP (2008) Preliminary study on the relationship between internal checks in earlywood within annual rings and the anatomical characteristics and density of *Eucalyptus nitens* [in Spanish]. Interciencia 33(11):829-834.

Mariani S, Poblete H, Torres M, Fernández A, Morales E (2006) Effect of the height in the anatomical and chemical properties of *Eucalyptus nitens* wood (Deane & Maiden) from Chile [in Spanish]. In proceedings of the X Reunión sobre Investigación y Desarrollo de Productos Forestales, November 14-17, 2005, Concepción, Chile.

McKenzie HM, Shelbourne CJA, Kimberley MO, McKinley RB, Britton RA (2003) Processing young plantation-grown *Eucalyptus nitens* for solid-wood products. 2: Predicting product quality from tree, increment core, disc, and 1-m billet properties. New Zealand, New Zealand. J For Sci 33(1):79-113.

McKimm J (1985) Characteristics of the wood of young fast-grown trees of *Eucalyptus nitens* Maiden with special reference to provenance variation. I. Variations in growth, strain and density associated with provenance. Aust For Res 15:207-218.

McKimm RJ, Ilic Y (1987) Characteristics of the wood of young fast grown trees of *Eucalyptus nitens* Maiden with special reference to provenance variation. III: Anatomical and physical characteristic. Aust For Res 17:18-28.

McKinley RB, Shelbourne CJA, Low CB, Penellum B, Kimberley MO (2002) Wood properties of young *Eucalyptus nitens, E. globulus*, and *E. maidenii* in Northland, New Zealand, New Zealand. J For Sci 32(3):357-379.

Medhurst J, Downes J, Ottenschlaeger M, Harwood C, Evans R, Beadle C (2012) Intra-specific competition and the radial development of wood density, microfibril angle and modulus of elasticity in plantation-grown *Eucalyptus nitens.* Trees (Berl) 26:1771-1780.

Purnell RC (1988) Variation in wood properties of *Eucalyptus nitens* in a provenance trial on the eastern Transvaal highveld in South Africa. S Afr For J 144:10-22.

Ramírez M, Rodríguez J, Peredo M, Valuenzuela S, Mendonça R (2009) Wood anatomy and biometric parameters variation of *Eucalyptus globulus* clones. Wood Sci Technol 43:131-141.

Rebolledo P, Salvo L, Contreras H, Cloutier A, Ananias RA (2013) Variation of internal checks related with anatomical structure and density in *Eucalyptus nitens* wood. Wood Fiber Sci 45(3):279-286.

Saranpää P (2003) Wood density and growth. Pages 87-117 *in* JR Barnett, G Jeronimidis, eds. Wood Quality and its Biological Basis. Blackwell Publishing, Victoria, Australia.

Sepulveda V, Perez N, Salinas C, Salvo L, Elustondo D, Ananias RA (2016) The development of moisture and strain profiles during pre-drying of *Eucalyptus nitens.* Dry Technol 34(4):428-436.

Shelbourne CJA, Nicholas ID, McKinley RB, Low CB, McConnochie RM, Lausberg MJF (2002) Wood density and internal checking of young *Eucalyptus nitens* in New Zealand as affected by site and height up the tree. N Z J For Sci 32(3):357-379.

Schweingruber FH (2007) Wood structure and environment. Springer Series in Wood Science, New York, NY. 284 pp.

Zobel BJ, van Buijtenen JP (1989) Wood variation its causes and control. Springer Series in Wood Science, New York, NY. 376 pp.